MEASUREMENTS AND SIMULATION OF WATER, NITRATE AND ATRAZINE MOVEMENT IN A SANDY SOIL CROPPED WITH SORGHUM

By

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DEDICATION

To the memory of my father,
Stephen P. Mbuya

To my mother,
Monica S. Mbuya

I will always love you

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MEASUREMENTS AND SIMULATION OF WATER, NITRATE AND ATRAZINE MOVEMENT IN A SANDY SOIL CROPPED WITH SORGHUM

By

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Chairperson: Dr. Kenneth J. Boote
Major Department: Agronomy

A field study was conducted to measure and simulate the amount and movement of water, nitrate N and atrazine within the root zone (0-90 cm) in a sandy soil cropped with sorghum (*Sorghum bicolor* (L.) Moench) at the University of Florida in 1991. The experiment was laid out as a 2 x 3 factorial design with two levels of N (100 and 300 kg N ha^{-1}) and three water management regimes (optimum irrigation, moderate irrigation and rainfed), randomized completely in four blocks. Atrazine was uniformly applied in all treatments at a rate of 1.12 kg a.i. ha^{-1}. Measurements of soil water, NO_3-N and atrazine content over time were done using neutron probe, Inductively Coupled Argon Plasma (ICAP) spectrometry and immunoassay, respectively. Leaching Estimation and Chemistry Model (LEACHM) and the CERES-Sorghum model were used to simulate

under field conditions, the amount and movement of water, NO_3-N and atrazine within the root zone, crop growth and crop N uptake.

Measured volumetric soil water content within 0-90 cm depth fluctuated between 5 and 13%. LEACHM underpredicted soil water content by an average difference of 3%. Soil NO_3-N and Br^- content showed great variability within treatments overtime. Approximately 58% of the applied 300 kg NO_3-N ha^{-1} was estimated to have leached beyond the root zone and 44% was absorbed by the crop during the growing season. LEACHM predicted 117 kg NO_3-N ha^{-1} were leached beyond 90 cm soil depth and 60 kg NO_3-N ha^{-1} was crop uptake during the season. Measured crop N uptake and N leached beyond 90 cm at harvest were 125 and 103 kg ha^{-1}, respectively. In treatment under optimum irrigation and 300 kg ha^{-1} of applied N, CERES-Sorghum predicted 136 and 182 kg ha^{-1} as leached N and crop N uptake, respectively. Leaf, stem and total dry matter accumulation were poorly predicted by CERES-Sorghum.

A large proportion of atrazine recovered from the soil over time was in the top 15 cm and sharply decreased with depth. Atrazine content within 0-90 cm decreased from 0.44 kg a.i ha^{-1} two days after application (DAA) to 0.1 kg a.i ha^{-1}, 26 DAA. Very small amount of atrazine was detected below 60 cm soil depth. Large application rates of fertilizer N are likely to leach into underground water, especially where the water table is shallow. Split fertilizer application and moderate irrigation could reduce leaching in sandy soils. Overall, the prediction of soil water and NO_3-N under field conditions by LEACHM and CERES-Sorghum were poor. Prediction of soil atrazine by LEACHM was good.

CHAPTER I

INTRODUCTION

Grain sorghum (*Sorghum bicolor* (L.) Moench) is grown mainly in the semi-arid areas of the tropics and subtropics. It is the fifth most important cereal in the world (Doggett, 1988). Water and nitrogen (N) are the most limiting soil factors in semi-arid tropical and subtropical regions where inadequate rainfall and low soil fertility limit crop production. On the other hand, N is a macro nutrient element that is required and utilized in large quantities by all green plants. In modern agriculture, large amounts of fertilizer N are applied annually to croplands in order to increase crop yields. In addition to fertilizer, a large arsenal of pesticides are used to control weeds, insects and diseases.

The availability and mobility of N in the root zone is highly influenced by water movement. Adequate water supply is essential for achieving potential yields of many crops. There is no substitute for N or water in the essential roles they perform in plant growth and development. Rainfall is the major source of agricultural water input, but in regions with inadequate and/or poorly distributed rainfall, irrigation provides supplemental water input. However, excessive N application and irrigation, especially on sandy soils with low water holding capacities, enhance N leaching beyond the crop root zone, thus contributing to potential pollution of surface and groundwaters. On the contrary, inadequate water and N supply can reduce crop yields.

Atrazine (*2-chloro-4-ethylamino-6-isopropylamino-s-triazine*) is one of the leading herbicides used in grain sorghum (*Sorghum bicolor* (L.) Moench) and maize (*Zea mays* L.) production in the United States and many developing countries where cereal production is predominant. It persists in soils for 3 to more than 12 months, depending on the dose applied, formulation, and environmental conditions such as rainfall, organic matter, and temperature (Andersen, 1983). In general, persistence in the soil is longer in arid than in humid regions. Despite the fact that atrazine is adsorbed to soil colloids and absorbed by crop roots, leaching still occurs. The extent of leaching is dependent on soil type, amount of herbicide applied and the volume of percolating water moving through the soil profile.

Although the benefits of N fertilizers and herbicides are well known, excessive use poses a threat to the environment and human health. In recent years, serious harmful effects associated with the use of agricultural chemicals came to light. As early as 1962, Rachel Carson warned the public of potential harmful effects of using large quantities of agricultural chemicals on large areas of croplands.

A significant challenge in production agriculture today is the development of satisfactory techniques that combine optimum production with protection of the environment. At present there is insufficient information, particularly in developing countries that specifically documents and characterizes crop production systems with regard to both agronomic factors (e.g. N-fertility level, pesticide use, water relations and yield) and the downward movement of solutes. Lack of government regulation and/or enforcement on the use of fertilizer and pesticides in many developing countries has a

likelihood of exacerbating the threat of environmental pollution and degradation specifically surface and groundwater

Fertilizer N has often been suggested as the primary source of nitrate (NO_3) in ground and surface water in many rural and suburban areas of developed countries where N fertilizers are heavily used and monitored. Likewise, many pesticides including atrazine have been found present in ground and surface water in several countries including the United States of America. Fertilizer and pesticide recommendations are developed with the intent of optimizing crop yield without accompanying studies on the possibility of leaching beyond the root zone (Koo et al., 1984; Singh and Tucker, 1988; Singh et al., 1990).

In view of the above, scientists, agricultural producers and the public should be concerned with the use and fate of fertilizers and pesticides in various agro-ecosystems. In order to establish guidelines for optimum agronomic and economic use of fertilizers, pesticides and water, management decisions should be based on the knowledge of fate and interactive effects of such agricultural inputs within the ecosystem. Understanding the interaction of the inputs under field conditions is important, particularly in sandy soils with low nutrient and water holding capacities. Collection of such information could help policy makers formulate government regulations for economic and safe use of agrochemicals. A call for detailed evaluation of the fate and impact of agrochemicals on the environment is therefore, not only prudent but compelling.

Modeling is increasingly being used as a tool for evaluating the fate of pesticides and fertilizers in soils. Solute transport and crop growth simulation models have been

developed and used to predict fertilizer-N and pesticide movement in soils, N uptake and crop response to various levels of inputs. Due to climatic and soil differences there is a need to test and validate some of the already existing models, modify them and/or develop new models if necessary.

Interest in the transport of chemicals in soils is motivated by the potential of agricultural and other chemicals (fertilizers, pesticides, industrial wastes) to move from the surface through the unsaturated zone toward the groundwater table (Leij et al., 1991; Gamerdinger et al., 1991) and consequently becoming potential pollutants.

In this study, the Leaching Estimation And Chemistry Model-LEACHM (Wagenet and Hutson, 1989; Hutson and Wagenet, 1992) and CERES-Sorghum model (IBSNAT-DSSAT[1], 1990; Tsuji et al., 1994a, 1994b) will be tested. The objectives of the study are 1) to characterize and quantify the amount and movement of applied NO_3-N and atrazine within the root zone at different water inputs over time, 2) to simulate under field conditions, the leaching of NO_3-N and atrazine in sandy soils using LEACHM and to compare predicted with actual observed data, 3) to simulate the growth of sorghum and soil N balance using the CERES-Sorghum model, and 4) to compare LEACHM and CERES-Sorghum model performance with respect to NO_3-N leaching and crop N uptake.

[1] International Benchmark Sites Network for Agrotechnology Transfer-Decision Support System for Agrotechnology Transfer

CHAPTER II

LITERATURE REVIEW

Large amounts of fertilizers and pesticides are used in modern agricultural production. Most of them are directly applied to the soil. Nitrogen is an essential element in all biological systems and is the most widely used element in fertilizers (FAO, 1990). It is a macro nutrient element that is required and utilized in large quantities by all crop plants. Water is indispensable wherever life exists. Water and N stress may induce reversible injury on crop plants by slowing or inhibiting metabolic processes or irreversible injury by killing cells (Levitt, 1980). Movement of water through soil determines how much fertilizer or pesticide remains accessible to crop roots versus how much is carried downward to the groundwater (Trautmann et al., 1985). Soil N deficit can be caused by deficit or excessive water.

Forms of N in Soils

The forms and transformations of soil N are well documented by many authors. There are three major forms of N in mineral soils: a) organic N associated with humus, b) ammonium N which can be retained by cation exchange sites of certain clay minerals, and c) soluble inorganic ammonium and nitrate compounds (Brady, 1990). The amount of N in the form of soluble ammonium (NH_4^+) and nitrate (NO_3^-) compounds is seldom

more than 1 - 2 percent of the total present except where large applications of inorganic N fertilizers have been made

Forms of N Used by Plants

Most of the N absorbed by plants is in either ammoniacal (NH_4^+) or nitrate (NO_3^-) form depending on the condition of the soil the kind of plant, and its stage of growth (Brady, 1990) In general, the presence of both ions seems favorable (Schrader 1984; Hageman 1984; Reddy et al , 1991) The nitrite (NO_2^-) ion is generally present in small quantities because it is so readily oxidized to the NO_3^- form

Nitrogen Uptake and Recovery

Nitrogen removed from different soils by sorghum ranges from 25 83 kg ha^{-1} (Kumar and Awasthi, 1977, Roy and Wright, 1974; Lanjewar and Khot, 1977) Cultivars producing large amounts of biomass remove greater quantities of soil N (Lanjewar and Khot, 1977) When soils are deficient in P, uptake of N can increase by 50% as a result of P application (Roy and Wright, 1974)

There is little published data on N recovery or N-balance aspects of sorghum in drylands (Vlek et al , 1981) Sorghum recovery values of N increased with P application in P deficient soils (Roy and Wright, 1974) and was markedly improved when N was applied in two or three splits in a high rainfall year (Venkateswarlu et al , 1978, ICRISAT, 1982, ICRISAT, 1983 Moraghan et al., 1983) This could be a combined effect of supplying N during periods of active crop growth, N absorption and presumably lower leaching losses

Crop Yield Response to Applied Fertilizer N

Crop yield is a quantitative character influenced by genotypic and environmental factors. For a given genotype, the components of reproductive yield are influenced by the need of the crop for carbon (C) and N at critical phenological stages (Simmons and Jones, 1985; Lemcoff and Loomis, 1986). The simplest response of a crop to applied N when that element is the first growth limiting factor is that dry matter yield will increase with increasing N rates up to a maximum, then to a plateau and finally decline with further N application. Dry matter yield is closely associated with amount of N in the soil up to a limit beyond which additional N has no advantage or has negative effects. Other factors such as soil type, form of fertilizer-N, time and method of application influence crop yield (Olson and Kurtz, 1982).

In order for the applied N to be available to the crop it must remain within the root zone during the growing season for crop uptake. The loss of fertilizer-derived N by leaching presents both an economic loss to the farmer and an environmental pollution (Lord and Bland, 1991). On the other hand, water deficit renders N unavailable to the crop. Management of water and fertilizer N are therefore inseparable.

Nitrogen-moisture Relationship and Sorghum Yield

All crops need both nitrogen and water. There is a significant positive interaction between fertilizer and moisture with respect to sorghum yield (Kanwar, 1978; Nagre and Bathkal, 1978; Reddy et al. 1978; Venkateswarlu and Rao, 1978). This interaction is reported to be stronger in an Alfisol than in a Vertisol (Kanwar, 1978). In an irrigation

experiment, application of 120 kg N ha^{-1} increased water-use efficiency by 30% (Singh and Bains, 1971) However, sorghum yields could be lower in seasons with excessive rainfall due to losses of N through leaching and denitrification and persistent cloudy weather which can reduce solar radiation for photosynthesis (Singh and Choubey 1972) These counteracting effects on crop growth and yield deserve more investigation

Fate of Nitrate N in Soils

The fate of the various forms of N in the soil is governed by a variety of interrelated and complex processes (Davidson et al , 1978) These processes involve inorganic (NH_4^+, NO_2, NO_3, N_2O, and N_2) and organic N forms which exist simultaneously in the soil These and other N substrates undergo continuous reversible and/or irreversible transformations owing to chemical and microbiological processes

The water soluble N species (NH_4^+, NO_2, and NO_3) are transported through the soil by molecular diffusion and more importantly by soil water The concentration of NH_4^+ and NO_3 in the soil is complicated further by absorption of plant roots The extent of water and N uptake by plants is determined in part, by the transpiration demand, which in turn is dependent upon plant species growth stage, and meteorological conditions (Davidson et al , 1978) The complexity of the soil-water-plant system is enhanced further by the fact that all of the above processes are transient in nature and occur simultaneously Therefore, a prerequisite to describing the fate of inorganic N forms in soil-water-plant system is a complete understanding of N transformation and transport processes

Nitrate Leaching

Nitrate leaching potential of a soil system depends primarily upon soil texture and structure, since they affect inherent hydraulic properties of the soil (Smith and Cassel, 1991), and on the dynamics of N transformations in soil. Nitrate is highly soluble and readily moves with soil water. Its availability and mobility within and beyond the root zone is highly influenced by the amount of water applied (rainfall and/or irrigation) and infiltration. Endelman et al. (1974) showed that rainfall or irrigation can rapidly move NO_3-N beyond the crop root zone. In contrast, leaching of NH_4 is retarded due to adsorption and ion-exchange reactions (Rao et al., 1975). Loss of NO_3 from agricultural soils by leaching increases with increasing soil NO_3 concentrations and water movement (Ferguson et al., 1988). Much of the inorganic N in soils occurs as nitrate, and is often at risk of leaching (Bergstrom and Jarvis, 1991). The magnitude of leaching is influenced by many climatic, edaphic, and agronomic factors (Godwin and Jones, 1991). Because of the leaching potential, excessive use of N fertilizers is a concern to environmental quality (Addiscott and Whitmore, 1991; Silvertooth et al., 1992).

Compared to other nutrients, NO_3 leaching is a major concern in Florida because of the predominance of sandy soils. Endelman et al. (1974) reported that 2.5 cm of water will move NO_3 about 15 to 20 cm in a loamy sand at field capacity. Heavy rainfall or excessive irrigation of about 10 cm is therefore estimated to move much of the NO_3-N well below the root zone of many crops in sandy soils (Graetz et al., 1973; Endelman et al., 1974).

Nitrate Fertilizer and Groundwater Contamination

Contamination of groundwater by agrochemicals (fertilizer and pesticides) is a serious environmental issue which has achieved center stage visibility in United States (League et al. 1988 Power and Schepers 1989 Weil et al 1990 USDA 1993) Interest in the transport of chemicals in soils is motivated by the potential of agrochemicals and industrial chemical wastes to move from the surface through the unsaturated zone toward the groundwater table (Ley et al. 1991, Gamerdinger et al 1991) and consequently becoming potential pollutants In many parts of the world groundwater is the main supply for drinking water (Huwe and van der Ploeg 1988) Concurrently, it has been observed that nitrate concentrations in groundwater, especially in shallow, unconfined aquifers, have increased.

Although the behavior of soil nitrogen has been studied extensively (Stevenson 1982), the exact interrelationships between agricultural practices like fertilization and the amount of nitrogen that is leached from the root zone, still are not completely understood (Huwe and van der Ploeg, 1988) As an effort against further occurrences of groundwater contamination, it is important to understand the complex interrelationships of soil-water-nitrate-crop interactions

The amount of fertilizer required by crops partly depends on the mobility of the plant available forms of the nutrient. Plants readily absorb N as NO_3 and/or the NH_4^+ form. The amount of water moving through the soil determines how much fertilizer remains accessible to crops versus how much is carried downward to groundwater (Trautmann et al., 1985). Leaching occurs more readily from coarse textured soils. The major physical disadvantage of sandy soils is their low capacity to retain water, thus requiring frequent rains or irrigations to keep the soil water content at levels that will prevent crop water stress. On the other hand, field studies by Watts and Hanks (1978), Watts and Martin (1981) and Martin et al. (1982) have demonstrated that one of the main causes of N deficiency in excessively irrigated plots is NO_3 leaching beyond the crop root zone. Inappropriate management of water and N in irrigated corn in Nebraska resulted in leaching of excess N from the root zone and contamination of ground water with nitrate-N (Olson et al., 1970; Schepers et al., 1991).

Nitrate-N contributes to groundwater pollution and is a threat to the environment (Nielsen et al., 1982; Watts and Hanks, 1978; McCasland et al., 1985). Excessive application of N and irrigation by large and small scale farmers, especially on sandy soils with low water holding capacities, has the potential to leach N beyond the crop root zone. Many farmers in most semi arid areas rely on irrigation for crop production. On the other hand, shallow wells provide drinking water. Such wells are highly vulnerable to pollution by nitrogen and other chemical pollutants.

The principal aquifers supplying drinking water for urban areas in Florida underlie agricultural areas. It has been estimated that 91% of counties in Florida are

served by public water in potentially contaminated areas (USDA 1991) Therefore agricultural producers in Florida must adopt suitable preventive measures to minimize contamination of groundwater from agrochemicals

The development of modern analytical methodology has made possible the detection of extremely low concentrations of chemicals (Jones, 1986) In United States, the federal allowable maximum contamination level (MCL) in drinking water is 10 mg L^{-1} (i e 10 ppm) for NO_3-N or 45 mg L^{-1} for NO_3 (USEPA, 1976 Stevenson, 1986) Since 1985 the upper limit for NO_3 concentration in drinking water in the European Common Market countries has been lowered to 50 mg NO_3 L^{-1} (Huwe and van der Ploeg, 1988) Unless otherwise stated, nitrate levels usually refer only to the amount of nitrogen (N) present (McCasland et al 1985)

Pesticide Use

The use of pesticides is an integral part of today s agriculture Pesticides are applied to crops to control weeds insects fungi mites, nematodes and other pests Sales of pesticide in the United States total approximately 1 1 billion pounds (500 million kilograms) annually (Ehteshami et al., 1991) Approximately 552 million pounds of active ingredients of pesticides were applied to crops in the United States in 1982 (OTA, 1984) Non-agricultural uses of pesticides include the elimination of unwanted vegetation from roadsides, railways, airfields, golf courses, forestry breaks and other areas as well as urban and suburban applications by homeowners (Rao and Allen, 1993)

A study by the National Academy of Sciences (1984) estimated that about 143,000 tons of hazardous wastes (including pesticides) are generated every day in the United States. Army (1988) estimated that about 300 million kilograms of pesticides are applied annually to United States crops. The use of pesticides, particularly herbicides, have increased significantly during the past four decades (Rao et al., 1983). These agrichemicals have contributed significantly to increased crop yields and in many cases have decreased production costs (Rao et al., 1983). However, the increased use of pesticides in conjunction with the growing number of leaking underground tanks and unavoidable chemical spills has produced both potential and actual deterioration of water quality in many regions (Petach et al., 1991). Unfortunately, pesticides are poisons and can be particularly dangerous when misused (Rao and Hornsby, 1989). Excessive use of agrichemicals poses a potential threat not only to the environment, but also to human health (USEPA, 1990).

Atrazine is one of the most prevalent herbicides extensively used for weed control in maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* (L.) Moench) production in the United States (Wollenhupt and Springman, 1990), and is widely used in many developing countries where tropical cereal production is predominant. The herbicide falls under the diamino-s-triazine family.

Predicting Fate of Pesticides in Unsaturated Soil Zone

With increasing awareness and concern for environmental quality, it is important that we consider not only the effectiveness of a pesticide, but also its persistence and

mobility in soil (Bergstrom et al., 1991). It is desirable to be able to estimate the fate of a pesticide applied to the soil surface. The fate is determined by a number of environmental processes, many of which operate in the unsaturated (vadose) zone of soil located between the soil surface and the groundwater (saturated) zone (Wagenet and Hutson, 1986). The vadose zone can be divided into a root zone of varying depth depending on crop type and age, and an underlying unsaturated zone of relatively diminished biological activity.

A number of transient processes affecting pesticide fate occur within the root zone, including water flow and subsequent pesticide displacement, plant extraction of water and pesticide, and chemical and microbiological processes of sorption and degradation (Wagenet and Hutson, 1986; Wagenet and Rao, 1985). These processes operate most strongly within the root zone and determine to a great degree the mass of pesticide available to exit the root zone to groundwater, and the amount of water available to transport the chemical. It is therefore important to estimate the fate of a pesticide under a specified set of soil, water, and chemical conditions.

The fate of a particular pesticide under a unique combination of environmental circumstances (e.g., soil type, rainfall, irrigation and application rate) can be best estimated by simultaneously considering all important processes and integrating them through a modeling approach (Wagenet and Rao, 1985). The evaluation of the potential for atrazine and other pesticides to contaminate ground water requires an understanding of transport mechanisms that occur in the field, and the capability to accurately represent these mechanisms in simulation models (Gaber et al., 1995).

Pesticide Leaching

Despite the fact that pesticides are adsorbed to soil colloids and absorbed by crop roots leaching still occurs. Agricultural practices that affect leaching include the amount of pesticide applied (Hall et al., 1972), the pesticide formulation (Wauchope, 1978) timing of application relative to seasonal rainfall or temperature extremes (Morton et al., 1989) the method of application (Bovey et al., 1978), crop residues (Dao, 1991), tillage practices (Baker et al., 1978) and the volume of percolating water moving through the soil profile as irrigation (Andersen, 1983 Troiano et al., 1990 USEPA, 1987). Climatic and soil conditions modify the amount of water that is available for downward flux through the soil profile (Ochs et al., 1983). Troiano et al. (1990) related the amount of atrazine leached to the amount of deep percolating water from irrigation

Pesticides and Groundwater Contamination

Groundwater vulnerability to contamination can be defined as the propensity for contaminants to reach some specified position in the ground-water system after their introduction at some point above the top of the uppermost aquifer (Rao and Alley, 1993). The use of pesticides has extensive potential for contaminating groundwater. Pesticides applied to the soil may migrate though the soil to the water table (Fetter, 1993). In fact pesticide contamination of groundwater has now become a major environmental issue (Rao and Alley, 1993). Reports of groundwater contamination by several pesticides and other organic pollutants have increased over the years (Pye et al., 1983; Rao et al., 1985). These reports of increasing incidence of pesticides and other toxic organic

pollutants in groundwater (Cohen et al. 1984, Pye et al. 1983) have prompted a number of laboratory and field experiments of the processes and factors influencing pesticide behavior in soils and groundwater (Rao et al., 1986).

Early concern for pesticide contamination of groundwater was raised with the discoveries in 1979 of aldicarb in groundwater in New York, and dibromochloropropane (DBCP) in California, the subsequent finding of these pesticides in groundwater in other states, and the widespread detection of another pesticide, ethylene dibromide (EDB), in groundwater in the early 1980s in California, Florida, Georgia, and Hawaii (Rao and Alley, 1993). However, pesticides were reported in groundwater prior to the 1979 discoveries (Richard et al., 1975). A review of occurrences of pesticide contamination of groundwater in the United States is reported by Hallberg (1989) and Ritter (1990). Contamination of groundwater is not limited only to chemicals used for agriculture (Anderson, 1987). Perchloroethylene (PCE) and trichloroethylene, solvents used extensively for dry cleaning and degreasing, have been found in municipal water supplies throughout the United States (Anderson, 1987).

At least 46 pesticides have been reported in groundwater in 26 states as a result of normal agricultural use (USEPA, 1988). A survey of 23 states in the United States found 17 pesticides, including atrazine, were present in groundwater (Cohen et al. 1986). Williams et al. (1988) found atrazine present in groundwater in 22 states of the United States of America. In a National Pesticide Survey (NPS), atrazine was one of the most commonly detected pesticides in groundwater in United States (USEPA, 1990, Wollenhaupt and Springman, 1990). According to the Florida Department of

Environmental Regulation (DER), all chemicals in the USEPA list are found in Florida (Shankland, 1985). Several researchers, including Hammond et al. (1981), Hammond and Bennett (1988) and Camp and Campbell (1988) stressed the re-evaluation of water management strategies in the Southeastern United States, due to the vulnerability of groundwater pollution by agricultural chemicals. The federal allowable maximum contamination level (MCL) in drinking water in United States is 3.0 parts per billion (ppb) for atrazine (USEPA, 1976; Stevenson, 1986).

Rainfall, Irrigation, Agrichemicals and Water Contamination in Florida

The physical property of the water resource in Florida is unique among the states (Saarinen and Lynne, 1993). Florida has a relatively flat topography, sandy soils and a highly permeable limerock substructure that all but eliminate the use of surface reservoirs for storage of rainfall. Alternatively, rainfall is effectively stored in the system of aquifers which underlie most of the state (Conover et al., 1984). Florida is thus highly dependent on its various aquifer systems for water supply, a water supply which is vulnerable to saltwater intrusion, degradation by chemical pollutants and overpumping. In a nutshell, a water supply which is in fact a common pool resource.

In general, there is limited data on the mobility of agricultural chemicals applied to the soil surface (Silvertooth et al., 1992). Excessive N and pesticide application, and irrigation, especially on sandy soils with low water holding capacities, promotes N and pesticides to leach beyond the crop root zone, thus contributing to groundwater pollution. Often times many farmers do not consider the consequences of excessive fertilizer

pesticide and irrigation application in relation to groundwater contamination. In the past 20 years, irrigated acreage in the Southeastern United States increased by more than 60%. The rapid expansion of irrigated agriculture on sandy soils has been attributed to the development of center-pivot irrigation systems (Cochran et al., 1983; Watts and Martin, 1981). The expansion and intensification of agricultural production on coarse textured soils has prompted increased application of N fertilizer in order to realize profitable yields. At the same time, higher temperatures coupled with humidity favor the rapid increase of pests (insects, weeds, diseases) and hence increased use of pesticides. Since inadequate water and N supply reduce crop yields, management decisions concerning N, pesticides and water inputs should be based on knowledge of the interactive effects of all inputs within the soil-crop system. Understanding the interaction and fate of agricultural inputs under field conditions is important, particularly in sandy soils with low nutrients and water holding capacities.

Evidence of Harmful Effects of Pesticides and Fertilizers on Humans and Animals

Although the benefits of N fertilizers and pesticides are well known, their excessive use poses a potential threat to the environment, livestock and human health. Fish kills, reproductive failure in birds, and acute illnesses in people have been attributed to exposure to or ingestion of pesticides (Rao and Hornsby, 1989). The U.S. Environmental Protection Agency (USEPA) has classified atrazine as a possible human carcinogen (Jourdan, 1993), whereas high level of NO_3 in drinking water, food and other sources is known to cause *methemoglobinemia* (blue baby) in infants and animals (Deeb

and Sloan, 1975; Aldrich, 1980; McCasland, et al., 1985). Methemoglobinemia is the most significant health problem associated with nitrate in drinking water.

Nitrate in drinking water starts affecting the health of the general populace at levels in the range of 100 to 200 mg/l nitrate-N (i.e., 100 to 200 ppm), but the effect on any given person depends on many factors. Some of the nitrate consumed can be converted in the body to nitrite, which under appropriate circumstances can combine with amines to form nitrosamines, well documented cancer causing substances (McCasland et al., 1985). Atrazine has been found to affect the metabolism of fresh water fish (Srinias et al., 1991).

Pesticide Management and Regulations

A significant challenge in production agriculture today, is the development of satisfactory techniques that combine optimum production with environmental protection. In order to ensure proper use and management of pesticides, a number of state and federal laws have been passed to protect groundwater and surface water quality (Rao, 1988). Some states, including Florida and California, have adopted regulatory standards for pesticides in groundwater that are more strict than those set by USEPA. In Florida, the Department of Agriculture and Consumer Services (DACS) regulates the registration and use of pesticides, the Department of Environmental Regulation (DER) oversees the disposal of hazardous wastes and monitors groundwater and surface water quality, and the Department of Health and Rehabilitative Services (DHRS) sets the drinking water standards on the basis of available toxicological information. These state agencies

coordinate the regulatory actions with their local and federal counterparts and amongst themselves

Water Flux

Flux density of water is simply defined as the mass of water moving through a unit cross-sectional area of soil in a unit time period. The basic relationship describing water flow through saturated materials was first postulated by Henri Darcy (Darcy, 1856), whereas basic equations describing water flow in unsaturated soils were presented in 1931 (Richards, 1931)

The ability to quantitatively describe field soil water fluxes is important for solving a wide range of agricultural and environmental problems (Buttler and Raha 1992). Soil water simulation models have been used to estimate crop irrigation water requirements (Norman and Campbell, 1983), to assess environmental fate of agricultural chemicals (Wagenet and Hutson, 1986), and to classify soils (Van Wambeke et al., 1986).

The water flux density in a vertical one-dimensional soil system is expressed according to Darcy's law as

$$q_w = -K\left(\frac{dH}{dz}\right) \quad \ldots\ldots\ldots\

combined with the continuity equation to become the Richards equation

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}[K(\theta)\frac{\partial H}{\partial z}] \quad \ldots\ldots (2)$$

where θ = volumetric soil water content ($L^3\ L^{-3}$), $K(\theta)$ = hydraulic conductivity dependent on water content, H = total hydraulic head (L), and t = time

In order to accomodate sinks like absorption of water by actively transpiring plant (or crop) Nimah and Hanks (1973) modified equation (2) to

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}[K(\theta)\frac{\partial H}{\partial z}] + A(z,t) \quad \ldots\ldots (3)$$

where A(z,t) is the term describing the rate of plant root extraction of water

For nonsteady flow, the flux of water at depth z can be expressed as

$$q_w(z) = q_w(z_0) - \frac{1}{\Delta t}\int_{z_0}^{z} \Delta\theta dz \quad \ldots\ldots (4)$$

where q_w = volumetric water flux ($L\ T^{-1}$), and it is assumed that no sources or sinks of water exist in the depth interval dz (Wagenet, 1983). Equation (4) is difficult to solve analytically for most initial and boundary conditions that apply to field cases. However, several approaches to estimate water flux under field conditions have been developed. These include: a) direct measurements with a soil flux meter as described by Richards et al., 1937; Ivie and Richards, 1937; Byrne et al., 1967, 1968; Byrne, 1971; Cary, 1968, 1970 and Dirksen, 1972, 1974, b) estimation from continuity principles which use measurements of water content as a function of depth and time in the profile to calculate

the flux from the continuity equation for soil water (Rose and Stern, 1965; Nielsen et al., 1973), c) prediction with numerical models where finite-difference and finite-element methods have been used to provide approximate solutions of Richards equation (Hanks and Bowers, 1962; Bresler, 1973), and d) estimation using scaling techniques whereby water flux is estimated as a function of spatially variable soil hydraulic properties (Warrick et al., 1977a, 1977b, Simmons et al., 1979, Bresler et al., 1979, Wagenet and Rao, 1983).

Although Darcy's law and Richards equation are popular approaches for describing water flow they, have some limitations (Hutson and Wagenet, 1992). First, the necessary data are not easily obtainable, especially hydraulic conductivity. Second, the numerical solution procedures are time-consuming, although more rapid procedures have been developed (Ross, 1990) which are based upon Newton Raphson solution techniques and which use longer time steps. Third, and perhaps most important limitation, Richards equation is applied assuming vertically homogeneous soils with no preferential flow path such as cracks, worm holes, root holes, or display of fingering phenomena (Hutson and Wagenet, 1992).

Solute Transport

Chemicals in solution can be transported within the soil profile by saturated and unsaturated water flows. Solutes in soils can either be displaced downwards to deeper depths or upwards by rising water table. For example, fertilizers and other soil amendments, organic and inorganic wastes, and soluble salts in water are all subject to

displacement once applied to the soil surface (Wagenet, 1983). The amount of solute displaced is influenced by physical and chemical processes related to water, solute and the soil (Wagenet, 1986).

The mechanisms responsible for solute transport are considered to be both physical (convection or mass flow) and chemical (diffusion) (Wagenet and Rao, 1985; Wagenet, 1986). When considered simultaneously, these processes have been summarized in the convective-dispersive, or miscible displacement equation.

$$J_s = J_D + J_C \qquad (5)$$

where J is the mass of solute transported through a cross-sectional area in a unit time, g cm^{-2} h^{-1}, and the subscripts S, D, and C represent total solute, solute transported by diffusion, and solute transported by convection, respectively. Alternatively, equation (5) could be written as

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial z^2} - v\frac{\partial c}{\partial z} \qquad (6)$$

where c = solute concentration (M L^{-3}), D = hydrodynamic dispersion coefficient (L^2 T^{-1}), incorporating both chemical diffusion and hydrodynamic dispersion, v = pore water velocity (L T^{-1}), and z and t are distance (L) and time (T), respectively. When water flow is transient and the solute is noninteracting, the above equation (Eq. 6) must be revised to accomodate the changing of soil water content and water flux density as follows

$$\frac{\partial(\theta c)}{\partial t} = \frac{\partial}{\partial z}\left(\theta D\frac{\partial c}{\partial z}\right) - \frac{\partial}{\partial z}(q_w c) \qquad (7)$$

where q_w = volumetric water flux ($L\ T^{-1}$).

The governing equation for one-dimensional unsaturated solute transport, subject to sorption and transformation is

$$\frac{\partial}{\partial z}[D(\theta,q)\frac{\partial(\theta c)}{\partial z}]-q\frac{\partial(\theta c)}{\partial z}\quad k\theta c\quad \frac{\partial(\theta c)}{\partial t}+\frac{\partial(\rho_b s)}{\partial t}=\phi(z,t). \quad \ldots \quad (8)$$

where **D** is the hydrodynamic dispersion coefficient, q is the soil water flux determined from equation (7) and Darcy's law, c is the solute concentration ρ_b is the bulk density of the soil, s is the concentration of solute in the sorbed phase k is the transformation rate coefficient, and $\phi(z,t)$ represents sources/sinks of solute

Coupled soil water flow and solute transport are simulated by sequential solution of Equations (7) and (8) using numerical techniques (finite element or finite difference) given the appropriate initial conditions, boundary conditions, and parameter values Application of this approach is often restricted due to the staggering data requirements (Loague et al , 1988) An understanding of the simultaneous movement of water and solutes in soils is essential for improved efficiency of soil-applied agrochemicals, prevention of groundwater contamination, waste disposal site management and wastewater renovation using soils (Davidson et al , 1983)

Sorption of Agrichemicals in Soils

Sorption accounts for adsorption and absorption It is the partitioning of chemical species (sorbate) between the solution (liquid) and sorbent (solid) phases If the chemical of interest is strongly adsorbed then only a small fraction of its original amount applied

will be in the solution phase and vice versa. Sorption is a major determinant factor affecting the mass of solute available in solution for advective-dispersive transport through a soil profile

Chemicals are either polar or nonpolar Nonpolar chemicals are mainly adsorbed by organic matter, whereas polar chemicals adsorb to clay surfaces (Jury et al , 1986, Wagenet, 1987) Many pesticides are nonpolar and their adsorption on soils is related to the organic carbon (OC) content of the soil

The partitioning of a solute between the liquid and solid phases is mathematically described by an expression called an adsorption isotherm (also called a sorption isotherm) The relationship could be linear or nonlinear The most applied equilibrium sorption isotherm is the Freundlich equation

$$S = K_d C^n \qquad (9)$$

where S = adsorbed concentration ($\mu g\ g^{-1}$), K_d = partition coefficient ($(\mu g^{1-n}\ ml^n)/g$)) and C = solution concentration ($\mu g/mL$), n = exponent. The exponent n may be less. equal or greater than 1.0. When the relationship is assumed to be linear, n = 1 and equation (8) becomes

$$S = K_d C \qquad (10)$$

Rao and Davidson (1980) discussed the errors associated with the assumptions of linearity, instantaneous equilibrium and reversibility of sorption A linear adsorption isotherm is generally valid when the equilibrium concentration of the solute is less than one half of its solubility limit

Although the partition coefficient, K_d, is unique to a given sorbate-soil

combination, it has been shown that when K_d is normalized for the organic carbon content of the soil the resulting value is independent of the soil type and can be considered to be a property of the chemical (Rao and Davidson, 1980, Nkedi-Kizza et al., 1983). A normalized partition coefficient, K_{oc}, is mathematically defined as

$$K_{OC}\% = K_d \times \frac{100}{OC} \quad \text{(11)}$$

where OC = organic carbon content of the soil (g/g). The practical significance of K_d in mathematical modeling is to determine retardation factor which affects the effective velocity of the chemical species of interest. Despite the fact that data collected on pesticide sorption raise questions on the simplified assumptions used, the approximation appears to be adequate for many practical applications (Rao et al. 1984, Green and Karickhoff, 1990).

Degradation of Pesticides in Soils

Pesticide degradation in the vadose zone involves both abiotic and biotic processes (Rao and Alley, 1993). During degradation, chemical pathways can lead to a transformation of the parent compound to production of intermediate metabolites. However, only biotic pathways result in complete mineralization of pesticides to carbon dioxide, water and other simple products. Quantitative data on degradation rates are limited (Scow, 1990) because 1) standard experimental protocols for measuring biodegradation are lacking, 2) the results are not comparable and apply only to a particular set of experimental conditions, and 3) the variables that control degradation rates are not well understood. Some compilations of degradation rate constants may be

found in Rao and Davidson (1980), Rao et al. (1984), Nash (1988) and Scow (1990). More recently, extensive compilation of degradation constants for pesticides (Wauchope et al., 1991) have been published. Published degradation rates are for particular values of temperature and soil water content. Biodegradation rates may decrease rapidly as soils dry, temperature of soil water decreases, and mass-transfer processes change (Scow and Hutson, 1992; Scow and Alexander, 1992).

Atrazine degrades to hydroxyatrazine, deisopropylatrazine, desethylatrazine and many secondary metabolites (Muir and Baker, 1978; Erickson and Lee, 1989). The primary step in atrazine degradation, whether microbial or chemical, is dechlorination or dealkylation (Erickson and Lee, 1989). Dechlorination occurs via hydrolysis reaction. Jordan et al. (1970) found atrazine hydrolysis to be 10 times faster with soil than without soil. Factors affecting atrazine degradation include pH, soil type, organic matter, soil moisture and pesticide concentration.

Understanding sorption, degradation, and transport of pesticides and other organic contaminants in soils and aquifers is essential to predicting their fate and transport in the environment (Rao et al., 1993). Lack of consideration of physico-chemical and biological processes may cause discrepancies between model predictions and experimental observations. For example, sorption likely reduces or inhibits biodegradation rates in soils (Stotzky and Rem, 1966; Madsen, 1985; van Loosdrecht et al., 1990), or decreases the amount of substrate available to microorganisms (Weber and Coble, 1968; Subba Rao and Alexander, 1982; Miller and Alexander, 1991; Wszolek and Alexander, 1979; Gordon and Millero, 1985; Dashman and Stotzky, 1986; Robinson et al., 1990; Weber, 1991; Smith et al., 1991).

Modeling Concept and Classification

Modeling is a mathematical representation of reality (Jones et al., 1987). It is an accepted scientific practice providing a mechanism for comprehensively integrating basic processes and describing a system beyond what can be accomplished using subjective human judgements (Hutson and Wagenet, 1992). Clarke (1973) categorized mathematical models into four major groups: stochastic-conceptual, stochastic-empirical, deterministic-conceptual, and deterministic-empirical. A model is regarded as stochastic if any of the variables in its mathematical expression are described by a probability distribution. A model is termed deterministic if all the variables are viewed as free from random variations. Models are called conceptual if their functional form is derived from consideration of basic processes, and empirical if it is not. In other words, empirical models are essentially direct descriptions of observational data (Thornley and Johnson, 1990). Mathematical models can also be classified from the viewpoint of the modeler or the user (Wagenet et al., 1988). Clarke (1973) represented the modeler's perspective of a model as:

$$q_i = f(p_{i-1}, p_{i-2}, \ldots, q_{i-1}, q_{i-2}, \ldots ; a_1, a_2, \ldots) + E_i \qquad (12)$$

where, q_i are output variables, p_i are input variables, a_n are system parameters, E_i is the residual error, and f is the functional form of the model. The functional form of the relationship can be either conceptual or empirical. The input and output variables, the system parameters and the residual error can be either deterministic or stochastic. From the user's perspective, Wagenet et al. (1988) suggested that models can be classified as either research models, action-agency models, or extension/farm user model. Research

models are in general complex integrated process oriented The typical user of a research model tend to be a modeler capable of theoretical development. Action-agency models generally incorporate simplified algorithms for the same processes included in research models, and they are primarily used by State and Federal agencies as planning and/or regulatory tools Extension/farm user models generally represent processes in very simplistic, non-quantitative terms These models are usually employed at the local level for making site specific management decisions (Wagenet et al 1988)

A fundamental goal of mathematical modeling is to simulate information that can be used to make predictions for real systems (Loague et al 1988) Models are usually intended to reflect, at an appropriate scale, those processes which we feel to be important for the application of the model (Hutson and Wagenet, 1991) Thornley and Johnson (1990) suggested that one day the connection between theory and experiment will be most efficiently made using the language of mathematics.

Modelling is increasingly being used as a tool for evaluating the fate of pesticides and fertilizers in soils (Wagenet and Rao 1985). Crop growth simulation models have also been developed and used to predict crop response to various levels of inputs Despite the tremendous model development effort, well defined procedures for testing models are not yet available (Loague et al 1988).

In this dissertation the Leaching Estimation And Chemistry Model-LEACHM (Hutson and Wagenet 1992) and CERES-Sorghum model (IBSNAT-DSSAT, 1990 Tsuji, et al., 1994a and 1994b) will be tested These models have potential for being

used as future management decision tools for agricultural production and/or environmental quality control

Model Validation

Validation of a simulation model involves the comparison of predicted response with actual experimental or system data not previously used in development, calibration or any parameter estimation of the model (Whisler et al., 1986, Jones et al., 1987, Thornley and Johnson, 1990). Singh (1991) listed four steps for model validation: i) measurement of experimental inputs required by the model, ii) measurement of actual system (or experiment) performance (output), iii) running the model to simulate the system (or experiment) and predict the output, and iv) analyze and compare simulated results with actual observed experimental data.

The practical objective of model validation is to determine whether the model is sufficiently accurate for its application as defined by the objectives and its adaptability to different environmental conditions. Burk (1986) believes that the validity of a model depends on the model's ability to meet certain application objectives defined by the modeler or user. The intended use of model output determines how stringent the criteria for model acceptance should be (Loague et al., 1988).

Disagreement among modelers and researchers has surfaced as to the relevance of model validation (Anderson, 1974; Teng and Gaunt, 1980). Some researchers argue that simulation models cannot be proven to be exact replica of reality (Neelankavil, 1986,

Burk, 1986) and at some level of resolution almost all models will fail (Goulding, 1979). Others pointed out that validation procedures are very subjective (Anderson, 1974; Dent and Blackie, 1979) and usefulness of a model may depend on who is doing the evaluation and how he/she wants to use it.

Many modelers consider model validation to be a continuous process (Dent and Blackie, 1979; Burk, 1986) and with time the confidence in a model is established as it is repeatedly compared to independent data during its application. The results from any one statistical criterion or graphical display may not be sufficient to pronounce a model as valid even if established levels of confidence are available (Loague et al., 1988). Taken independently, each validation method can be limited by stringent assumptions, such as independence, equality of variance, and normality. If one or more assumptions are violated, then the sole reliance on the method is suspect. A model should only be considered validated if a set of performance tests are met. A generalized procedure for testing computer simulation models, such as the index of validity proposed by Gilmour (1973), may provide the type of combined assessment that is currently unavailable. The index of validity is composed of three sub-indices which test: i) stability, ii) predictive ability and iii) sensitivity to major assumptions.

Modeling Solute Transport

Modeling is increasingly being used as a tool for evaluating the movement and fate of pesticides (Wagenet and Rao, 1985; Addiscott et al., 1985; Davidson et al., 1978,

Hutson and Wagenet, 1989) and fertilizers in soils. Many different approaches have been taken to model solute movement in soils, ranging from very simple non mechanistic models to complex finite difference models (Addiscott and Wagenet 1985).

Deterministic, mechanistic models of solute movement based upon miscible displacement theory (Nielsen and Biggar, 1962) have been the most widely used modeling approaches in soil science over the last 30 years (Hutson and Wagenet 1992). The complexity and variability of physical and chemical processes which govern the movement of chemicals through soil profile often prohibit accurate simulation of solute leaching (Knighton and Wagenet, 1987). As a result, stochastic models which incorporate uncertainty into model prediction as an attempt to deal with the variability of naturally occuring systems have also been developed. One stochastic process which has been successful in modeling naturally occurring phenomena in many disciplines is the Markov process (Feller 1950; Bailey, 1964. Chiang 1980, Fan et al., 1982, Nassar et al., 1982). The Markov process requires that only the present value of the time-dependent random variable be known to determine the future value of the random variable. However, deterministic, mechanistic models are still the most widely used. The inherent complexity of the crop root zone and the dynamic nature of plant uptake of water and nutrients and pesticides sometimes defies an exact mathematical description. An understanding of the physiological characteristics of crops and their needs for water and nutrients is at best incomplete (Davidson et al., 1978).

The increased use of fertilizers and pesticides in modern agriculture has produced deterioration of water quality in many regions (Petach et al , 1991) Because of the difficulties involved in obtaining field measurements of pesticide leaching to groundwater predictions of pesticide movement based on solute transport model simulations are being relied upon more frequently to serve as guidelines during the development of pesticide regulatory policies Field experimentation with pesticides can be both hazardous and expensive, therefore models are useful for interpreting limited field data and extending the conclusions to other management and environmental situations (Hutson et al , 1988)

Solute Transport Models

Many models dealing with fertilizer and/or pesticide transport in the soil have been developed and documented The enormous computing power provided by personal computers (PCs) has made it possible for scientists and researchers to develop simple steady-state models, e g PESTAN (Enfield et al , 1982) and very complex process oriented models like LEACHM (Hutson and Wagenet, 1992) Below is a description of a few of the transport models

SESOIL (The Seasonal Soil Compartment model) was developed for the EPA as a screening model to simulate long term fate of pesticides in the soil (Donigan and Rao 1986a, 1986b)

NITROSIM (Nitrogen Simulation model) simulates transient water and N movement in the soil profile, transformation of N including mineralization, nitrification, and immobilization, and water and N uptake by plants (Rao et al., 1984)

MOUSE (Method Of Underground Solute Evaluation) is a management model and training tool for students and professionals developed at Cornell University (Steenhuis et al., 1987). The model can simulate solute movement in the vadose zone as well as in unconfined aquifer

PRIZM (Pesticide Root Zone Model) was developed by the U.S. Environmental Protection Agency (Carsel et al., 1984). The model is capable of simulating water and chemical fluxes over many years of historical or synthetic daily weather data and is intended for field use. The model accounts for runoff and erosion by using the SCS curve number equation (Williams and LaSeur, 1976) and modified Universal Soil Loss Equation (Wischmeier and Smith, 1978), respectively. PRIZM can simulate multiple applications of a given pesticide each year for several years of continuous climatic records. Effects of agricultural management and cropping practices can also be simulated

CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) is a field scale nonpoint source model for predicting sediments, nutrients and pesticide losses with surface runoff from agricultural management systems (Knisel, 1980)

GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) is a field-scale hydrology, erosion/sediment yield, and chemical transport model (Leonard et al., 1987). GLEAMS predicts runoff using SCS curve number method, and erosion is predicted using a modified Universal Soil Loss Equation.

NFLOOD (Rao et al., 1984) is a nitrogen simulation model that describes simultaneous partitioning, transformation, and transport of N in flooded soils.

Nitrogen Modeling

Several nitrogen models characterized by varying degrees of complexity have been reported in the literature. Bresler and Laufer (1974) simulated the movement of nitrate in a homogeneous soil profile in the presence of NO_3 production (nitrification) but did not consider plant uptake of water or nitrogen or any other nitrogen species. Saxton et al. (1977) modeled NO_3 movement and dissipation in fertilized agricultural lands but did not include representation of any other fertilizer form of nitrogen. Davidson et al. (1978) developed research and management-type models of nitrogen fate in the root zone, with the latter intended to be used by those willing to accept simplifying assumptions of water and solute processes in the field.

The interest in simulation models for nitrogen transport and transformation, especially with regard to NO_3 pollution of groundwater (Mehran and Tanji, 1974; Donigan and Crawford, 1976; Davidson et al., 1978; Tanji and Gupta, 1978; Frissell and Van Veen, 1981; Tanji, 1981; 1980; Rao et al., 1982), and the concern that N_2O may

contribute to the depletion of the ozone layer (McElroy and McConell 1971, Johnston, 1972 Delwiche and Bryan, 1976) prompted many researchers to emphasize their modeling effort in understanding the transient processes N undergoes in the soil-water plant continuum.

The description of nitrogen transport and transformation under field conditions depends upon accurate representation of physical, biological and chemical processes (Wagenet and Rao, 1983) Water flow and solute displacement under non-steady flow conditions nitrogen transformations by enzymatic or bacterial pathways plant uptake of water and nitrogen, and ion adsorption during transport all act to determine the distribution of nitrogen within the soil profile Modeling efforts must consider all these processes in a fundamental, mechanistic manner

Crop Models

For over twenty years scientists and engineers have been developing process-oriented simulation models of various crops (Tsuji et al., 1994a, 1994b) Many of the crop models simulate development and growth processes Some of the models are able to correctly predict crop phenology dry matter accumulation (leaf, stem, root, pod, seed), leaf area index (LAI), seed yield, and other parameters at different levels of inputs Just to mention a few, PNUTGRO (Boote et al., 1986), and SOYGRO (Wilkerson et al., 1983, Wilkerson et al., 1985, Jones et al., 1989) are crop growth simulation models developed at the University of Florida Crop models under the

CERES family include Maize, Wheat, Sorghum, Pearl Millet, Barley, and Rice (Ritchie et al., 1989, Tsuji et al., 1994a, 1994b). It is not my intention to list all the crop simulation models that have been developed for different crops world-wide today, but it is worth mentioning that many scientists are still involved in developing and evaluating models for different crops under different cropping systems.

Strategy evaluation can be performed with all models that are incorporated in the IBSNAT-DSSAT project (DSSAT, 1989; Tsuji et al., 1994a, 1994b). Strategy evaluation is a versatile, flexible and powerful tool that can be used to evaluate strategies rapidly. The user defines his/her objectives in terms of biological yield or net returns, then develops strategies to achieve the defined objectives and finally analyze the strategy using a Strategy Analysis program (see Chapter 5 of DSSAT User's Guide, Version 2.1, 1989; Tsuji et al., 1994a, 1994b). The strategy evaluation helps the user to make agricultural decisions based on economic risks associated with production and marketing.

Leaching Estimation And Chemistry Model (LEACHM)

LEACHM is the acronym for Leaching Estimation And Chemistry Model (Wagenet and Hutson, 1989) that refers to five versions of a one-dimensional finite difference model designed to simulate the movement of water and solutes through both layered and non-layered soil profiles. Darcy's law is used as the fundamental approach for water flow, and when it is combined with the continuity equation, produces a description of transient vertical water flow. LEACHM describes water regime and the

chemistry and transport of solutes in unsaturated or partially saturated soils to a depth of about two metres (Hutson and Wagenet, 1992). The five submodels of LEACHM are LEACHN, LEACHP, LEACHC, LEACHB and LEACHW.

LEACHN describes nitrogen transport and transformation while LEACHP simulates pesticide movement and degradation. The version LEACHC describes transient movement of inorganic ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, SO_4^{2-}, Cl^{-}, CO_3 and HCO_3) whereas LEACHW deals with water flux, and LEACHB describes microbial population dynamics. There is a main program for all of the five submodels that initializes variables, calls different subroutines and performs mass balancing. Subroutines deal with data input and output, time step calculation, evapotranspiration, water flow, solute movement, sources and sinks (e.g. degradation, transformation, volatilization, microbial growth), chemistry, leaf and root growth, temperature, and solute absorption by plants.

LEACHM is intended for both laboratory and field use. Although LEACHM can be used in a wide variety of field applications, the limitations and assumptions of the model must be recognized. The model does not include a surface flow component; consequently, runoff is not predicted. The movement of solutes through the soil matrix is assumed to result from a combination of convective and dispersive fluxes. LEACHM has no provision for rapid convective fluxes via macropores (e.g. worm holes or other structural formations) which may result in considerably greater movement of solute compared with flow which occurs strictly through the matrix.

All versions of LEACHM (i e LEACHN, LEACHP, LEACHC, LEACHB and LEACHW) require the following inputs, which are read from data files constructed appropriately for each version

a) soil properties and initial conditions for each soil segment. This includes i) water content or water potential, ii) hydrological constants for calculating retentivity and hydraulic conductivity or particle size distribution, iii) appropriate chemical contents and soil properties for each version

b) soil surface boundary conditions of i) irrigation and rainfall amounts and rate of application, ii) mean temperatures iii) potential evaporation (weekly totals)

c) crop data i) time of planting, ii) soil and plant water potential limits for water extraction by plants

d) other constants used in determining lower boundary conditions, time steps dispersion and diffusion coefficients, chemical reactions and transformations and output details

Hutson and Wagenet (1991) advised that the absence of retentivity and conductivity data should not deter users or prompt them to embark on time-consuming and expensive data collection projects Chemical transport is often relatively insensitive to these values Within reasonable limits of soil properties, water fluxes in field profiles are largely determined by surface boundary fluxes Water content distributions approached after equilibrium may vary from soil to soil but net downward fluxes depend

mostly on the balance between rain, evapotranspiration and runoff, non of which is controlled primarily by soil hydraulic properties. It is therefore possible to estimate both retentivity and the conductivity, with little loss of accuracy, when simulating many field conditions.

Since LEACHM was first released in 1987, it has been modified several times to accomodate more details and processes governing water flux and solute transport. The model has been used to evaluate the fate and leaching of pesticides and nitrogen in California, New York and Florida (Hutson et al., 1988; Troiano et al., 1990, Pennell et al., 1990). Chemicals evaluated included simazine, diazinon, bromide, atrazine, aldicarb and nitrogen. Troiano et al. (1990) reported that LEACHM could fairly predict the movement of atrazine under four methods of irrigation (sprinkler, basin, furrow and dip).

CERES-Sorghum Model

Cereal crop models assembled and distributed by IBSNAT using DSSAT software are generically known as CERES models (Tsuji et al., 1994a, 1994b). Six cereal crops covered by CERES models are maize, rice, sorghum, wheat, pearl millet and barley. CERES-Sorghum is a process-oriented, management-level model of sorghum (*Sorghum bicolor* (L.) Moench) crop growth and development that also simulates soil water balance and nitrogen balance associated with the growth of sorghum (Ritchie et al., 1989). The model uses a minimum of readily available weather, soil, and crop genetic inputs.

To simulate sorghum growth, development, and yield, CERES-Sorghum takes into account the following processes: a) phenological development, especially as it is affected by genotype and weather; b) extension growth of leaves, stems, and roots; c) biomass accumulation and partitioning; d) soil water balance and water use by the crop, and e) soil nitrogen transformations, uptake by the crop, and partitioning among plant parts.

In recent years, the IBSNAT project has incorporated crop models into its program for international agrotechnology transfer. This project uses models of several different crops, which has required the adoption of a standard format for inputs and outputs from the models. Model input and output structures are described in detail in Technical Report 5 (IBSNAT, 1986) and DSSAT v3, Vol. 1 and 2 (Tsuji et al., 1994a, 1994b).

Unlike LEACHN, the N version of CERES Sorghum is designed to predict the effects of cultivar, planting density, weather, and soil water upon growth and yield, plant nutrient (N, P, K) uptake and soil N balance. Strategy evaluation is also possible with CERES-Sorghum.

Why Simulation Modeling ?

Simulation modeling is not a substitute for traditional experimental data collection but a compliment. Models are intended to reflect, at an appropriate scale, those processes which we feel to be important for the application of the model. Objectives of

many modelers and/or users have varied from understanding mechanisms of processes (plant growth, solute transport in soils and plants), to assisting in management and decision making (Tsuji et al. 1994a, 1994b; Wagenet, 1991a, 1991b). Models can enable us to examine scenarios that are not worth subjecting to experiment.

In principle, the determination of nitrate and atrazine contents in the soil and subsequent groundwater contamination could be routinely solved by soil and water sampling and analysis method. However, this approach is labor-intensive, time consuming and expensive. Often times, it is difficult to take samples from shallow or stony soils. Still worse, many samples and results would be needed before general advice or conclusions could be derived. In contrast, simulation modeling will achieve more or less the same conclusion using less resources (labor, machinery and time). Furthermore, some experimental measurements are not only difficult to take but dangerous, hence the use of models. Some phenomena take many years before their effects are evident, so it is always good to be able to forecast and give early warning. Examples of such long-term phenomena include weather, long term global climate trend, and contamination of aquifers.

In this study, simulation models will be evaluated against actual field measurements as an attempt to see how close we can predict leaching of NO_3-N and atrazine in sandy soils. Based on the results of predicted versus actual field measurements, the models could be recommended as complimentary decision making and management tools in the use of nitrogen fertilizers and pesticides.

CHAPTER III

MATERIALS AND METHODS

The study was divided into a series of field and laboratory experiments, followed by computer simulation model testing.

Field Experiment

Site Description

A field trial was conducted in Gainesville at Unit 2 of the University of Florida Irrigation Research and Education Park (29° 38' N and 82° 22' W), during April-July, 1991 growing season. The soil type at the experimental site is classified as a Millhopper fine sand, a member of the loamy siliceous, hyperthermic family of Grossarenic Paleudults (Calhoun et al., 1974; Thomas et al., 1985). The soil had particle size distribution of 92% sand, 5% silt and 3% clay at 0-25 cm depth and 94% sand, 3% silt and 3% clay at 25-60 cm depth. Measurements of pH in 2:1 water to soil were 5.0 and 5.7 at 0-25 and 25-60 cm soil depths, respectively. Organic carbon content was 0.76 and 0.18% at similar depths. The preceding crop was maize.

Experimental Design

The experiment was laid out as a 2 x 3 factorial, with two levels of nitrogen (N) and three water management regimes replicated four times. The two N levels, N_0 and

N_1 were 50 and 150 kg N ha^{-1}, respectively, whereas the three water management regimes were optimum irrigation (W_0), moderate irrigation (W_1) and rainfed (W_2). Optimum and moderate irrigations were based on relative visual signs of crop wilting in the afternoon (1300 - 1500 hrs). Irrigation water was applied to optimum irrigation treatments whenever the crop started to show signs to wilting. Plots under moderate irrigation were irrigated when sorghum leaves started to roll due to wilting. Plot size was 14 m x 14 m.

Furadan (*2,3-dihydro-2,2-dimethyl-7-benzofuranyl methylcarbamate*) was uniformly broadcasted and incorporated into the experimental unit as a nematicide at a rate of 10 kg ha^{-1} on April 18. Nitrogen fertilizer in form of potassium nitrate (13% N and 44% K) was uniformly broadcasted and incorporated into N_0 and N_1 plots at a rate of 50 and 150 kg ha^{-1}, respectively, on April 17 (Table 3.1).

On April 22, sorghum (*Sorghum bicolor* (L.) Moench cv. Savanna 5) was sown at an inter- and intrarow spacing of 90 and 5.6 cm (20 plants m^{-2}), respectively, using a manual planter. Two days later (April 24), 25 and 75 kg N ha^{-1} of supplemental N-fertilizer in form of KNO_3 was added to N_0 and N_1 plots, respectively. Supplemental N-fertilizer application was prompted by the fact that 67 mm of rain fell between April 17 (day of first fertilizer application) and April 23 (Table A.1). A third dosage of supplemental N-fertilizer (25 and 75 kg N ha^{-1}) was applied on June 4, making the total N applied to N_0 and N_1 plots amount to 100 and 300 kg N ha^{-1}, respectively (Table 3.1). Sodium bromide (NaBr) solution was sprayed as a tracer for water and N movement in the soil at a rate of 45 kg Br ha^{-1} on April 26. This was achieved by dissolving 579 g of NaBr in 18 liters of water and evenly spraying on a 10 m x 10 m area within a plot.

Atrazine (*2-chloro-4-ethylamino-6-isopropylamino-s-triazine*) was applied at a rate of 1 12 kg a i ha^{-1} as a post-emergence herbicide on April 29, three days after crop emergence Whenever necessary supplementary hand-weeding was employed to keep the experiment weed-free A mixture containing 1 12 kg a.i ha^{-1} of Lannate [*s-methyl-N (methylcarbamoyl) oxy) thioacetumidate*] was applied as needed to control armyworm (*Heliothis amigera*) and corn earworm (*Helhothis zea*)

Table 3 1 Dates and amounts of fertilizer N applied to sorghum

Date	Treatments	
	Low N	High N
	kg ha^{-1}	
April 17	50	150
April 24	25	75
June 04	25	75
TOTAL	100	300

Field Instrumentation

One week after crop emergence, 30 transducer-equipped tensiometers were installed in plots 201 and 202 (N_1W_0 and N_1W_1) at 15, 30, 45, 60 and 90 cm depths The transducers were connected to a multiplexer switch which was connected to a data logger (21X Micrologger) programmed to read and record soil water potentials at 30 min intervals

A second set of manually-read tensiometers were installed in all plots at 30 and 60 cm depths (two tensiometers per plot) Aluminium neutron access tubes 4 8 cm in

diameter, were inserted into the soil to a depth of 110 cm, one in each plot. Each access tube was covered with a rubber stopper to keep out irrigation water and rain.

Soil Sampling

Soil core samples were collected at random from all 24 plots at 0-15, 15-30, 30-45, 45-60, and 60-90 cm depth increments using a core sampler, 2.8 cm in diameter, on May 1, May 24, June 6 and July 1. Samples were immediately put in ziploc plastic bags and stored at 4 °C (refrigerated) until analyses of bromide, NO_3-N, NH_4-N, atrazine and water content.

Soil Water Content Measurements

Soil water content was measured in all plots every other day using a Troxler Soil Moisture Neutrol Probe Model 3222, starting one week after planting until sorghum reached physiological maturity. Soil moisture measurements were taken at 23, 30, 45, 60, and 90 cm depths between 0900 and 1100 hours local time.

Soil Water Potential Measurements

Soil water potentials were estimated daily in all plots at 30 and 60 cm depths using manually read tensiometers. Measurements were taken between 1400 and 1500 hrs local time.

A separate detailed soil water potential study was conducted in plots 201 and 202 (N_1W_2 and N_1W_1) using transducer-equipped tensiometers. Measurements were taken at

30 min intervals at 15, 30, 45, 60, and 90 cm depths, from one week after crop emergence until physiological maturity. Water potential data were automatically recorded onto a computer cassette recorder (Tandy CCR-82), and later uploaded into a personal computer (PC) and converted into ASCII files. The ASCII files were finally imported into a spreadsheet (Quattro Pro 5.0) for further sorting and interpretation.

Crop Growth Analysis

Samplings for growth analysis were conducted weekly, starting one week after crop emergence until physiological maturity. Sorghum plants were harvested from an area of 1.0 m^{-2} in each plot (approximately 20 plants). Two plants were sub-sampled for i) leaf area (LFAREA), ii) leaf dry weight (LFWT), iii) stem dry weight STWT), iv) panicle dry weight (PNWT) and v) seed dry weight (SDWT). All samples were oven-dried at 70° C for 2 to 5 days to determine dry weight. Total dry weight (TDW) was determined as 18 plant (remainder) dry weight plus the dry weight of the two plant components.

Leaf area was measured using a LI COR 3100 leaf area meter (planimeter). Fraction leaf (FRLF), fraction stem (FRST) and fraction panicle (FRPN) were computed from the two-plant sample as follows,

$$FRLF = \frac{\text{Leaf dry wt.}}{\text{Plant dry wt}} \quad (13)$$

$$FRST = \frac{\text{Stem dry wt.}}{\text{Plant dry wt.}} \quad (14)$$

$$FRPN = \frac{\text{Panicle dry wt.}}{\text{Plant dry wt}} \quad (15)$$

Leaf area index (**LAI**) was calculated as,

$$LAI = FRLF \times SLA \times TDW \quad (16)$$

where SLA is specific leaf area computed as

$$SLA = \text{leaf area/leaf weight} \quad (17)$$

Leaf dry weight (LEAF), stem dry weight (STEM) and panicle dry weight (PANICLE) were respectively computed as

$$LEAF = FRLF \times TDW \quad (18)$$

$$STEM = FRST \times TDW \quad (19)$$

$$PANICLE = FRPN \times TDW \quad (20)$$

Weather Data

Weather conditions (daily maximum and minimum air temperature, rainfall, total solar radiation, photosynthetically active radiation, and mean soil temperature) at the experimental site were electronically recorded throughout the experimental period (April - July) using a Minimum Weather Data Set Recorder (LI-COR LI-1200 weather station). A tipping bucket rain gauge to monitor and record the amount, date and time of rainfall was installed at the site. The rain gauge was important to estimate the intensity of rainfall.

Major Field Events

A chronological summary of the major field events is presented in Table 3.2. Although the experimental site was visited daily, only the major events are reported.

Table 3.2 Summary of major field events at the experimental site

Date	Event/activity
04/16/91	First soil sampling
04/17/91	Fertilizer N application (50 and 150 kg ha^{-1})
04/18/91	Application of Furadan (10 kg ha^{-1} broadcast)
	Harrowing
04/22/91	Irrigation to all plots (to settle the soil for planting)
	Planting (sorghum)
04/24/91	Crop emergence
	Supplementary fertilizer N application (25 and 75 kg ha^{-1})
04/26/91	Bromide application (45 kg ha^{-1})
04/29/91	Application of atrazine (1.12 kg ha^{-1} a.i.)
05/01/91	Soil sampling
05/03/91	Irrigation (all plots)
05/04/91	Field instrumentation installed (transducers, tensiometers, neutron
	access tubes, etc.)
05/07/91	Crop growth sampling
05/14/91	Crop growth sampling
05/21/91	Crop growth sampling
05/24/91	Soil sampling
05/28/91	Crop growth sampling
06/04/91	Crop growth sampling

Table 3.1 continued

Date	Event/activity
06/05/91	Supplementary fertilizer N application (25 and 75 kg ha^{-1})
06/06/91	Soil sampling
06/11/91	Crop growth sampling
06/12/91	Irrigation (W_0 plots)
06/15/91	Irrigation (W_0 plots)
06/18/91	Crop growth sampling
06/21/91	Irrigation (W_0 and W_1 plots)
06/26/91	Crop growth sampling
07/01/91	Soil sampling
07/02/91	Crop growth sampling
07/09/91	Crop growth sampling
07/16/91	Crop growth sampling
07/23/91	Crop growth sampling
07/25/91	Soil sampling
07/31/91	Crop growth sampling
08/01/91	Harvesting

Laboratory Analyses

Plant Tissue N Analysis

Plant components from the oven-dry growth analysis sub-samples were ground in a Wiley mill through a 1mm steel mesh screen for measurement of crop tissue N

concentrations. Ground samples weighing 0.3 g were digested using a modification of the aluminum block digestion procedure of Gallagher et al. 1975. Catalyst used was 3.2 g of 9:1 of K_2SO_4 $CuSO_4$ and digestion was conducted for 4 hours at 400 °C using 10 ml sulphuric acid (H_2SO_4) and 2 ml hydrogen peroxide (H_2O_2). Ammonia in the digestate was determined by a semi-automated colorimeter (Hambleton, 1977). Tissue N and crude protein (CP) are reported as percentage on a dry matter basis (Table A.2). Vegetative (leaf + stem) N concentration and vegetative N content were respectively computed as

$$\text{Veg. \%N} = \frac{(\text{frac leaf x biomass x leaf \%N}) + (\text{frac stem x biomass x stem \%N})}{(\text{frac leaf x biomass}) + (\text{frac stem x biomass})} \quad (21)$$

and

$$\text{Veg. N} = \text{frac leaf x biomass x leaf \%N} + \text{frac stem x biomass x stem \%N} \quad (22)$$

Soil Bromide Analysis

Bromide was extracted from the soil using 1:1 methanol deionized distilled water. Twenty ml solution of 1:1 methanol deionized distilled water were added to 10 g of soil, shaken for 2 hours and then left to settle overnight in a refrigerator. Standard solutions of 4, 10 and 25 ppm Br^- were prepared by dissolving NaBr in deionized distilled water. A reference solution of 10 ppm Br^- was used.

Bromide concentrations in supernatant soil solution samples were analyzed using Dionex Ion Chromatograph (IC) equipped with Dionex Conductivity Detector 4000i. The conductivity detector was connected to an external integrator/recorder. There was an autosampler (Dionex automated sampler) attached to the IC, so samples were

automatically injected into the IC. A solution of 1.80 mM Na_2CO_3 and 1.70 mM $NaHCO_3$ was used as an eluant and 25 mN H_2SO_4 as a regenerant. The integrator was set at maximum absorbance peak of 220 nm.

Supernatant solution samples were taken from the refrigerator and allowed to come to room temperature before injecting into the IC. The analysis protocol involved a batch of three standards, fifteen samples and one reference solution. The autosampler had a maximum load of 88 samples and allowed loading up to four batches at once. Bromide anions were separated on the HPIC-AS4A anion exchange separator column with the carbonate/bicarbonate buffer eluant. The run time was approximately 7 min. The calibration curve (or equation) to compute the concentrations of Br⁻ for each batch of 15 samples was based on the three standards in that batch. Standards were chosen based on the range of Br⁻ concentration expected in the samples.

Soil N Extraction and Analysis

Nitrogen was extracted from the soil samples using 20 ml of 2 mM Na_2SO_4 for every 10 g (approximately) of soil sample, shaking overnight using a reciprocating shaker and finally taking 10 ml of clear supernatant solution after sedimentation. The supernatant solution samples were analysed for NO_3-N and NH_4-N using Inductively Coupled Argon Plasma (ICAP) spectrometry and/or Ion Chromatography. The ICAP spectrometry consisted of i) an emission source powered by a 2 kW crystal-controlled radio frequency (RF) generator, ii) an optical system which focused light from the plasma emission source onto an entrance slit to a photomultiplier tube (PMT) detector

The detector converted light energy to electrical current. The magnitude of the current is proportional to light intensity. A computer system controlled collection of the integrated charge information from the optical system and converted this value to concentration units. The computer system controlled many other parameters associated with the emission source, the optical system, set up the analytical methods, stored and retrieved analytical data.

Soil Atrazine Extraction and Analysis

Atrazine was extracted from soil samples using 20 ml of 1:1 solution of methanol deionized distilled water for every 10 g of soil. The mixture was shaken for two hours using a reciprocating shaker and then allowed to settle overnight in a refrigerator. After settling, 5 ml of clear supernatant solution was put into vials for atrazine analysis. Atrazine concentrations in the supernatant solutions were quantified using an immunoassay method developed by Ohmicron (1991). Since the immunoassay procedure was enzyme based, the supernatant solution samples were further diluted by 50:1 using deionized distilled water in order to avoid denaturing of the enzyme. Four standards of 0, 0.1, 1.0, 5.0 and one control of 3.0 parts per billion (ppb) of atrazine, respectively, were used for the calibration equation (or curve) to determine the atrazine content in the soil.

Test tubes labeled for standards, controls and samples were arranged in a rack. Using a micropippete, 200 μL of standards, control and supernatant solution samples were pippetted into the individual labeled test tubes followed by 250 μL of Atrazine

Enzyme Conjugate Immediately, 500 μL of throughly mixed Atrazine Antibody Coupled Magnetic Particles were gently added into each test tube, vortexed at low speed (to minimize foaming) for 1 to 2 sec and then incubated for 15 min at room temperature (20 - 25 °C). During incubation, a color reagent was prepared by mixing equal volumes of Chromogen and hydrogen peroxide solution in a clean beaker. The color reagent was stable for only one hour. After 15 min of incubation, the rack holding the test tubes was combined with a magnetic base. All test tubes on the rack were firmly pressed against the magnetic base for 2 min in order for the Atrazine Antibody Coupled Magnetic Particles to separate from the solution. After 2 min, while holding the rack onto the magnetic base, the combine assembly was slowly inverted over a sink and the test tube contents was poured out. The test tubes were kept inverted and their rims gently blotted on several layers of paper towel. One ml of washing solution was added into each test tube using a repeating pippette, and after two minutes the contents were poured into a sink and the tube rims were again dried using paper towel as previously explained above. This step (rinsing) was repeated twice and then the rack (with test tubes) was separated from the magnetic base. Then 500 μL of the color reagent was added into each test tube, vortexed for 1 to 2 sec and then incubated for 20 min at room temperature (20 - 25°C). After 20 min, 500 μL of stopping solution (sulfuric acid) was added to each test tube to stop the color reaction. The solution color produced in each test tube was read by an RPA-I™ RaPID Photometric Analyzer which allowed light readings (absorbance) to be converted into digital readout. All readings were taken within 15 min after adding the stopping solution. Actual pesticide concentrations in the soil were calculated as

$$\text{photometer reading} \times \frac{\text{vol. of methanol}}{\text{wt. of soil}} \times \frac{\text{vol. of extract} + \text{vol. of diluent}}{\text{vol. of extract}} \quad (23)$$

Atrazine Adsorption Isotherms

Atrazine adsorption experiments were conducted to determine the adsorption coefficient (K_d) as a function of soil depth. Soil samples were collected from 0-15, 15-30, 30-45, 45-60, and 60-90 cm profiles and then oven dried at 105 °C for 24 hours. Solutions containing 1, 5, 10 and 15 ppm of analytical grade (98.7%) ^{12}C atrazine (Ciba-Geigy Co., Greensboro, NC) were made in a background solution of 0.01N $CaBr_2$ using deionized distilled water as a solvent. The ^{12}C atrazine solutions were then spiked with 0.05 ml of radioactive ring-labeled ^{14}C atrazine solution of known counts per minute (cpm).

A volume of 10 ml of the different concentrations of spiked atrazine solutions were added to 10 g of oven dry soil samples, shaken for 4 hours and then centrifuged at 1000 rpm for 5 min using Beckman Model J2-21 centrifuge. A 0.5 ml aliquot of the supernatant solution from each soil sample was analyzed for ^{14}C radioactivity using a scintillation counter (Beckman LS-100c Liquid Scintillation System). All four concentrations of atrazine were run in duplicate and blanks (with no soil) were also run. Scintillation count was proportional to the amount of atrazine in solution. The difference between scintillation count of the radioactive atrazine solution before adding soil samples and of supernatant solution from soil samples was attributed to adsorption. The equations below show how the values were obtained for amount of atrazine adsorbed (Se) and atrazine in solution at equilibrium (C_e).

$$f = \frac{^{12}C_{sl}}{^{14}C_{sl}} \quad \left(\text{i.e. } \frac{\mu g}{ml} \times \frac{ml}{cpm} = \frac{\mu g}{cpm}\right) \qquad (24)$$

$$S_e = \frac{2fV[C_o - B - \{C_e + BS\}]}{m} = \frac{2fV(^{14}C_o - ^{14}C_e - B)}{m} \qquad (25)$$

$$C_e = 2f([^{14}C_o - BS) \quad (26)$$

where S_e amount of atrazine sorbed at equilibrium, C_e is concentration of atrazine in solution at equilibrium, V is volume of atrazine solution, m is mass of soil, f is ratio of radioactivity per weight of atrazine ($^{12}C_o$ and $^{14}C_o$ are initial concentrations of non-radioactive and radioactive atrazine solutions, respectively), B is scintillation blank for soil, BS is scintillation blank for solution. Atrazine adsorption across the concentration range was described by the Freundlich linear equation:

$$S_e = K_d C_e \quad (27)$$

Graphs of S_e versus C_e for different soil depths were plotted, where $\Delta S_e/\Delta C_e$ is the adsorption coefficient K_d.

Degradation of Atrazine in Soil

A degradation study was done to determine the rate of disappearance of atrazine from the soil. Soil samples were divided into two categories, topsoil (0-25 cm deep) and subsoil (25-61 cm deep). An equivalent of approximately 10 mg kg^{-1} of atrazine, based on weight of soil at field capacity were dissolved in methanol and plated on the bottom of a 250 ml Erlenmeyer flasks (4.08 ml of 400 mg L^{-1} pesticide). The Erlenmeyer flasks were then placed under a hood to allow the methanol to evaporate. Soil samples containing an equivalent of 150 g oven-dry soil were added to the flasks and water was added to bring them to field capacity. Field capacity was assumed to be 10% moisture content by weight. To ensure a homogeneous distribution of the pesticide in the soil, the soil samples in the flasks were thoroughly stirred with a stainless steel spatula for 5 min.

After stirring soils were immediately sampled and analyzed for initial atrazine content, M_o. Subsequent samplings were done at 1, 2, 4, and 7 days and weekly thereafter. The experiment was done in two replicates. Extraction of atrazine from soil samples was done using 80:20, methanol:1M monochloroacetic acid buffer. Concentrations of atrazine in the extracts were determined by high pressure liquid chromatography (HPLC) using a Waters 490 Programmable Multiwavelength detector, a Spectra Physics 8780 autosampler and a Spectra Physics 4290 computing integrator.

The biological degradation study assumed the first order degradation rate equation:

$$M = M_o e^{-k_1 t} \quad (28)$$

where

M = mass of pesticide (μg) at a given time, t,

M_o = initial mass of pesticide (μg) at t_o,

k_1 = degradation rate coefficient (day^{-1}), and

t = time (day)

Rearranging Eq. 28,

$$M/M_o = e^{-k_1 t} \quad (29)$$

Taking natural logarithm of each side,

$$\ln (M/M_o) = -k_1 t \quad (30)$$

gives a linear equation describing degradation.

Application of Leaching and Chemistry Model (LEACHM)

LEACHM was used to predict movement of water, bromide, atrazine and nitrate-N within the rooting zone (0-90 cm). A sample of input data files for the water (LEACHW), pesticide (LEACHP) and nitrogen (LEACHN) versions of LEACHM are shown in Tables B.1, B.2 and B.3, respectively. LEACHW, LEACHP and LEACHN were used to characterize the movement of water, atrazine and nitrate within the rooting zone, respectively.

All required input data were entered into the different versions of LEACHM as illustrated in the sample input data files shown in Tables B.1, B.2 and B.3. Model input data included:

1. Soil properties and initial conditions with depth,
    a) soil bulk density
    b) soil particle density
    c) depth boundaries
    d) soil water potential
    e) soil water content
    f) hydraulic conductivity
    g) nitrate content
    h) atrazine content
    i) Campbell's water retention and conductivity constants, a and b
2. Soil surface boundary conditions;
    a) irrigation (frequency, duration and rate)

b) rainfall (daily data)

c) pan evaporation (daily or weekly)

d) evapotranspiration (daily or weekly)

3 Chemical properties

a) solubility

b) adsorption coefficient

c) transformation rate constant

d) degradation rate constant

e) vapor density

4 Crop data

a) crop(s) planted

b) date of germination

c) date of emergence

d) date of crop maturity

e) fraction crop cover

f) relative root depth

g) upper and lower soil water potentials for water extraction by plants

5 Other constants or parameters (e.g. diffusion coefficients, time step)

Soil water retention parameters were estimated using **RETFIT** program. RETFIT is a water retention regression model which generates hydraulic conductivity values (K_θ) for various soil water content (θ). The program uses Campbell's water retention equation (1974),

$$h = a\left(\frac{\theta}{\theta_s}\right)^{-b} \quad \text{.....(31)}$$

which was later modified by Hutson and Cass (1987) to,

$$k = \frac{\alpha(1-\theta/\theta_s)^{\frac{1}{2}}(\theta_e/\theta_s)^{+}}{(1-\theta_e/\theta_s)^{\frac{1}{2}}} \quad (32)$$

where θ_s is volumetric water content at saturation, θ_e specified volumetric water content, and a and b are constants. Constant a is sometimes referred to as air-entry value. In order to use Equation (31) or (32), values of hydraulic conductivity for defined water content values (θ) or matric potential (h) must be specified.

Use of CERES Sorghum Model

Crop, soil and weather data were entered into the CERES-Sorghum model input files according to DSSAT version 3 format (Tsuji et al., 1994a, 1994b). Genetic coefficients for the cultivar sown (Savanna S) were not available in the genotype database of CERES-Sorghum, therefore Dr. Boote and I estimated the coefficients (P1 - thermal time from seedling emergence to end of the juvenile phase during which the plant is not responsive to changes in photoperiod; P2O - critical photoperiod or the longest day length at which development occurs at a maximum rate, P2R - extent to which phasic development leading to panicle initiation is delayed for each hour increase in photoperiod above P2R and P5 - thermal time from beginning of grain filling to physiological maturity) for the purpose of this study. Soil profile properties were based on the description of Millhopper fine sand found in the DSSAT soil database file. Based on the physical properties of the soil chosen, CERES Sorghum requires as inputs 1) soil water

content at saturation, ii) lower limit of plant extractable water, and iii) the drained upper limit.

Crop management data input included i) cultivar planted, ii) planting method and depth, iii) inter and intra row spacing, iv) dates, type and amounts of irrigation water applied v) dates, amount and type of fertilizer applied, vi) incorporation of crop residue, time and depth of incorporation, and residue nutrient concentration (N, P), vii) pest and disease control. This crop management data entered in the DSSAT File X is shown in Table B 5

Statistical Analyses

Experimental data were subjected to routine statistical analyses using GLM, ANOVA and REG procedures of the Statistical Analysis System (SAS Institute Inc., 1988) to establish differences, similarities and correlations among treatments

CHAPTER IV

RESULTS AND DISCUSSION

This chapter will mainly report on measured field and laboratory data. Simulated results will be presented and related to actual measured data in Chapter V.

Field Data Acquisition

The experimental site was visited daily for various data collection throughout the study period. A few times unexpected rainfall interfered with field activities such as measurements of soil water content, soil and crop growth samplings. In some cases such activities had to be rescheduled. Observations of water potential from tensiometers installed 30 and 60 cm deep were erratic and insufficient for the purpose of computing water flux through the root zone.

Weather Conditions

Weather conditions at the experimental site during the study period are shown on Figures 4.1 and 4.2. Between April 1 and July 30, the experimental site received a cumulative rainfall of 629 mm, with monthly values of 153, 138, 135, and 203 mm for April, May, June and July, respectively. The precipitation was fairly well-distributed. In general the season was wetter than normal, probably due to an *el nino* phenomenon. Monthly mean maximum air temperatures were 28.9, 31.9, 32.7 and 33.3 °C for April

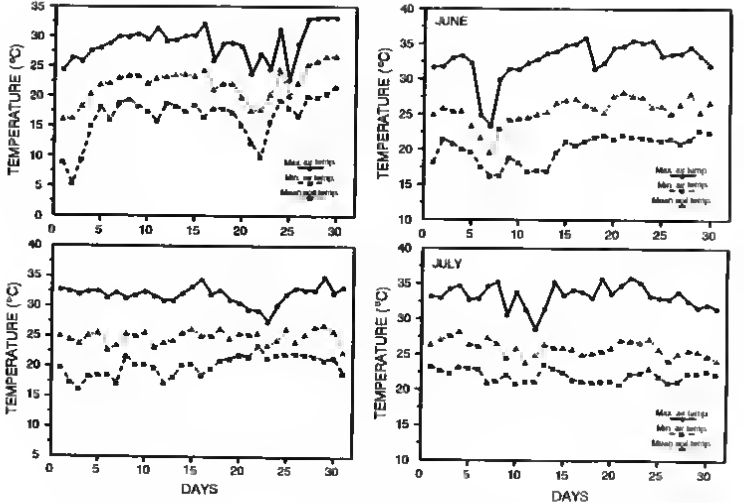


Figure 4.1 Daily air and soil temperatures at the Irrigation Research and Education Park during 1991 growing season

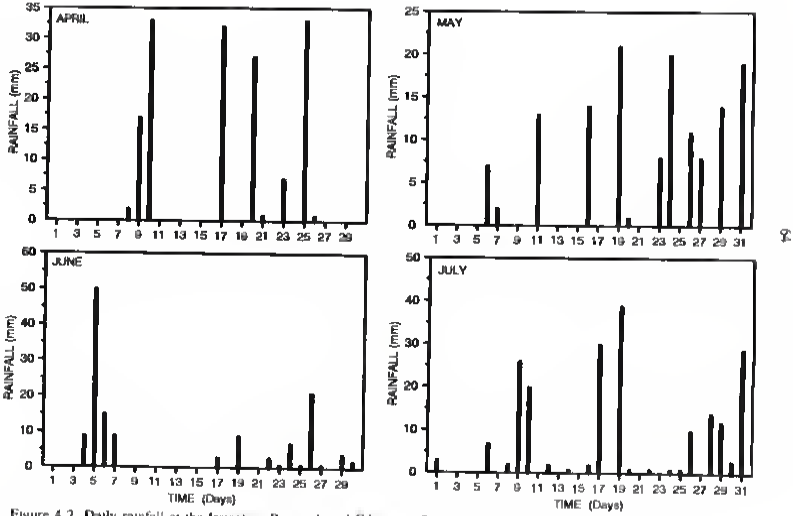


Figure 4.2 Daily rainfall at the Irrigation Research and Education Park during 1991 growing season

May, June and July, respectively, whereas monthly mean minimum air temperatures were 16.5, 20.2, 20.1 and 22.0 °C for the same period. Mean soil temperature at 1 m depth was always higher than the minimum air temperature.

The field experiment had three water management regimes, namely optimum irrigation (W_0), moderate irrigation (W_1) and rainfed (W_2) but due to abundant rainfall during the experimental period, the two irrigation treatments were virtually masked by the rainfall. Irrigation data are summarized in Table 4.1. Both rainfall and temperature were favorable for crop growth and soil microbial activities.

Table 4.1 Dates and amounts of irrigation water applied to the field experiment.

Date of irrigation	Irrigation†		Rainfed
	W_0	W_1	W_2
	mm		
04/22/91	4.3	4.3	-
05/03/91	12.0	12.0	-
06/12/91	19.0	0.0	-
06/15/91	19.0	0.0	-
06/21/91	19.0	19.0	-

† W_0 = optimum irrigation
W_1 = moderate irrigation

Crop Growth Response

Leaf Area Index (LAI)

Irrigation treatments had no significant effect ($\alpha \leq 0.05$) on LAI due to heavy rains during the growing season. Measured LAI were therefore averaged over irrigation treatments and presented as influenced by fertilizer treatments (Fig. 4.3). There was a linear increase in LAI between 22 and 57 DAP. Significant differences ($\alpha \leq 0.05$) in LAI due to applied N were evident starting 43 DAP until physiological maturity. In response to N deficiency, tissue N from older leaves started to be mobilized and exported to younger leaves at an earlier stage resulting to early leaf senescence. This was manifested by the relatively low LAI (< 3) in all treatments. Increase in LAI started to slow down earlier in treatments receiving 100 kg N ha^{-1} because N deficiency was more severe, causing lower (old) leaves to senesce quickly.

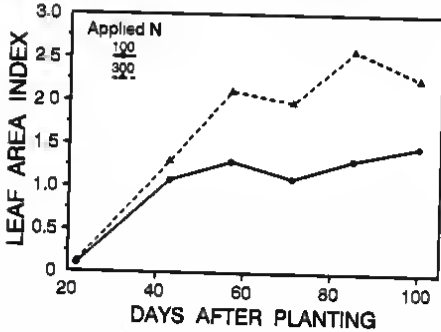


Figure 4.3 Leaf area indices of sorghum as influenced by two rates of fertilizer N

Specific Leaf Area (SLA)

Figure 4 4 shows a linear decrease ($r^2 = 0.99$) in SLA between 22 and 77 DAP. There was no significant difference ($\alpha \leq 0.05$) between treatments throughout the growing season. Different light intensities have been shown to influence SLA (Pearce and Lee 1969, Mbuya 1990), but light was not a limiting factor in this study. Decrease in SLA over time was indicative of leaf thickening. Just before anthesis (62 DAP) SLA started to decrease at a decreasing rate and after 71 DAP it started to increase. Increase in SLA (leaf thinning) coincided with the reproductive phase, suggesting export of N and other assimilates from leaves to reproductive sinks.

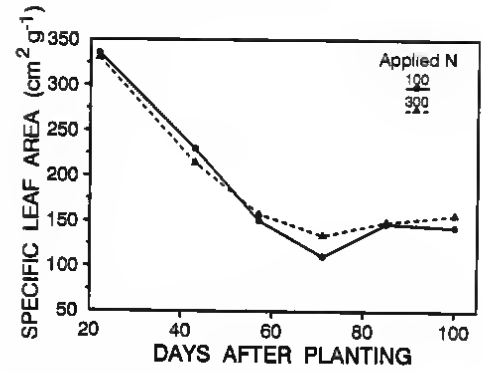


Figure 4 4 Specific leaf area of sorghum as influenced by two rates of fertilizer N

Fraction Leaf and Fraction Stem

Fraction leaf and fraction stem had distinct opposite trends over time (Figs 4 5 and 4 6) Applied fertilizer N had no significant effect ($\alpha \leq 0\ 05$) on either fraction leaf or fraction stem, suggesting that the proportions of dry matter partitioned to different plant components are dependent on phenology nad genotype, and not very sensitive to N supply Fraction leaf and fraction stem of common beans (*Phaseolus vulgaris* L) grown under to different light intensities were also not significantly different (Mbuya 1990)

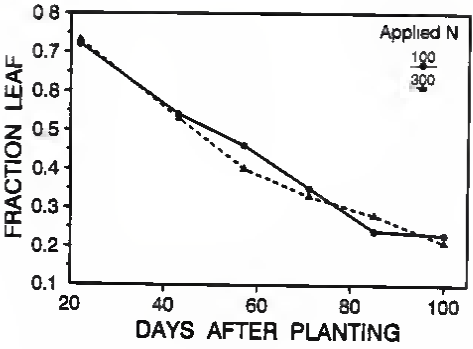


Figure 4 5 Fraction leaf of sorghum as influenced by two rates of fertilizer N

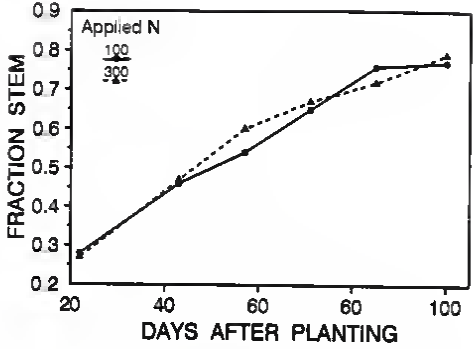


Figure 4.6 Fraction stem of sorghum as influenced by two rates of fertilizer N

Leaf Dry Weight

Leaf dry matter accumulation increased linearly ($r^2 = 0.99$) between 20 and 58 DAP, three days before flowering (Fig. 4.7). The crop receiving 100 kg N ha^{-1} had a significantly ($\alpha \leq 0.05$) lower leaf dry weight than that receiving 300 kg N ha^{-1} starting 37 DAP until physiological maturity. The rate of leaf growth started to decrease during the reproductive phase (60 DAP to harvest) due to less partitioning of assimilates to the leaves and/or export of assimilates from leaves to reproductive sinks. Nitrogen deficiency also contributed to early leaf senescence which partly accounted for rapid decline of leaf dry weight during reproductive phase.

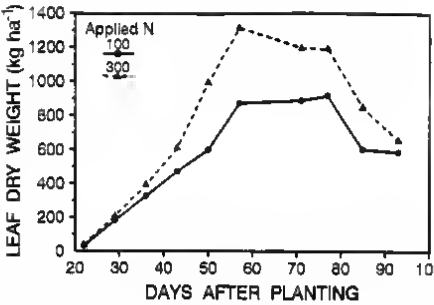


Figure 4 7 Leaf dry matter accumulation in sorghum under two rates of fertilizer N, averaged over water management treatments

Stem Dry Weight

A lag phase of dry matter accumulation was evident over the first 37 DAP in all treatments (Fig 4 8) Within this period there was no significant ($\alpha = 0.05$) difference in stem dry matter accumulation between 100 and 300 kg ha^{-1} of applied N Significant difference in stem dry weight in response to fertilizer differential was observed starting 37 DAP until physiological maturity There was also linear growth ($r^2 = 0.99$) between 37 and 57 DAP for the 300 kg N ha^{-1} treatments and 37 to 77 DAP for treatments receiving 100 kg N ha^{-1} A decrease in stem growth rate was noticed between 57 and 77 DAP just before the beginning of reproductive phase Decrease in stem growth rate just before flowering was indicative that the crop was starting to divert assimilates to developing reproductive sinks

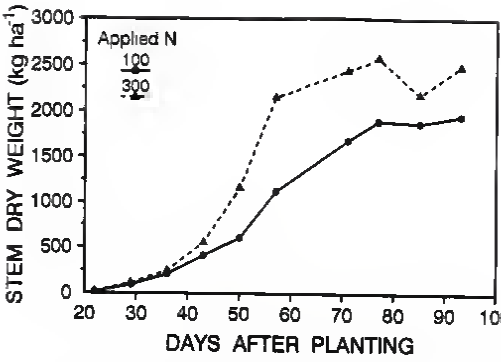


Figure 4 8 Stem dry matter accumulation in sorghum under two rates of fertilizer N averaged over water management treatments

Total Dry Matter (TDM) Accumulation

Above ground dry matter accumulation was significantly different ($\alpha \leq 0.05$) between 100 and 300 kg ha^{-1} of applied N starting 43 DAP (Fig. 4 9). There was a sharp linear ($r^2 = 0.99$) increase in TDM between 43 and 57 DAP followed by a slower linear phase between 57 and 77 DAP. Total dry matter accumulation was strongly influenced by the amount of applied N and it was indicative of available N within the root zone and crop N uptake.

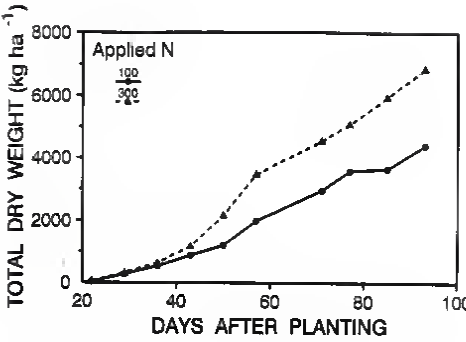


Figure 4 9 Total dry matter accumulation in sorghum under two rates of fertilizer N averaged over water management treatments

Grain Yield

Table 4 2 summarizes mean grain yield of sorghum at harvest The significant difference ($\alpha = 0.05$) in grain yield between fertilizer treatments was not a surprise since yield of any crop is limited by one or more factor(s) that affect dry matter production In many cases the most limiting factors are soil fertility and moisture In this case soil N was the most limiting factor

Table 4.2 Grain yield of sorghum at harvest as affected by irrigation and fertilizer N

N rate	Irrigation Trt	Grain yield*
-- kg ha^{-1} --		---- kg ha^{-1} ----
100	Optimum	3493 a†
100	Moderate	2890 a
100	Rainfed	3230 a
300	Optimum	5318 b
300	Moderate	5346 b
300	Rainfed	4751 b

* 0% moisture content (dry wt.)

† Means followed by the same letter within a column are not significantly different at 5% probability level using Duncan's Multiple Range Test.

Crop N Uptake

Leaf N Concentration

Leaf N concentration is shown in Fig. 4.10. The crops receiving 100 and 300 kg N ha^{-1} had no significant difference ($\alpha \leq 0.05$) in leaf N concentration throughout the growing season. A sharp decline in N concentration from 4.8 to 1.8% was observed between 22 and 43 DAP, after which it remained fairly constant (43 to 85 DAP) and then declined. Decline in percent N could be attributed to increased structural carbohydrates (e.g. cellulose) as the leaves continue to grow and mature.

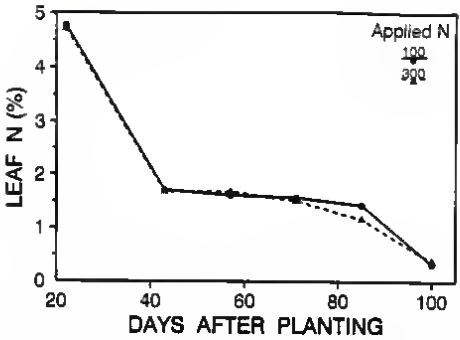


Figure 4.10 Sorghum leaf N concentration as influenced by fertilizer N, averaged over irrigation treatments

Stem N Concentration

There was a rapid decline in stem N concentration from 4.2 to 0.5% between 22 and 43 DAP after which it remained fairly constant until physiological maturity (Fig. 4.11). There were no significant differences ($\alpha \leq 0.05$) in stem N concentrations between 100 and 300 kg ha^{-1} of applied fertilizer N. Initial higher N concentrations could be attributed to the fact that at early stages of development, the sorghum stem was mainly composed of leaf sheaths. In general, leaves had higher N concentrations than stems.

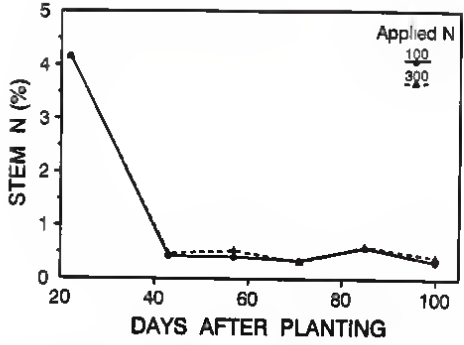


Figure 4.11 Sorghum stem N concentration as influenced by fertilizer N averaged over irrigation treatments

Vegetative (leaf + stem) N Concentration

Figure 4.12 summarizes the trend of vegetative N concentrations between fertilizer treatments over time. Although the trends changed over time, there was no significant difference ($\alpha \leq 0.05$) in vegetative N concentrations between 100 and 300 kg ha^{-1} of applied N at all stages of crop development. Vegetative N sharply declined from about 4.6 to 1.1 % between 22 and 43 DAP and remained fairly constant thereafter

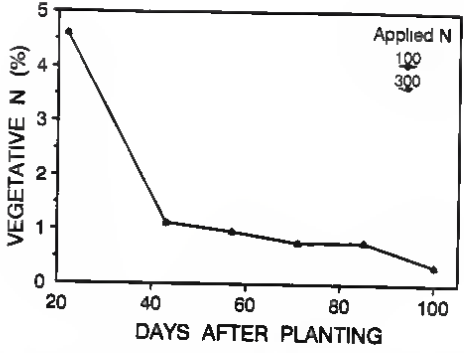


Figure 4 12 Sorghum vegetative N concentration as influenced by fertilizer N, averaged over irrigation treatments

Vegetative (leaf + stem) N Accumulation

Vegetative N accumulation is a function of vegetative N concentration and dry weight (Eq 19) Vegetative N content could be used as an estimate of crop N uptake for measurements taken before flowering Only 20% (30 kg ha^{-1}) of the 100 kg ha^{-1} applied fertilizer N and 16% (50 kg ha^{-1}) of the 300 kg ha^{-1} applied fertilizer N had been accumulated in vegetative parts by 87 DAP (Fig 4 13)

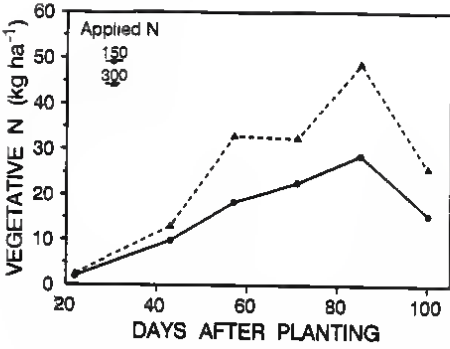


Figure 4 13 Vegetative N accumulation in sorghum as influenced by fertilizer N

Soil Water

Soil Water Content

Volumetric soil water content estimated by neutron probe between May 13 and July 15 is presented in Figs 4 14 and 4 15 Fertilizer N had no effect on soil water content, therefore, reported volumetric soil water content were averaged over N treatments Despite heavy rains during the experimental period observed soil water content hardly exceeded 13% at any depth within 0-90 cm Poor water holding capacity across the root zone (0-90 cm) was a good indication that large inputs of water into the soil drained to deeper horizons along with any chemical in solution phase

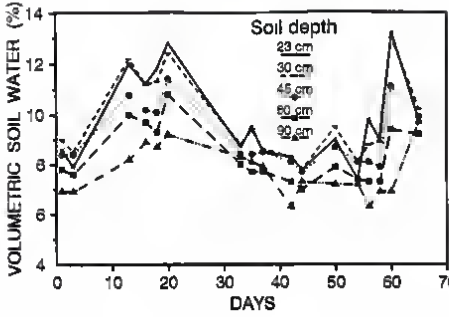


Figure 4 14 Volumetric soil water content at different depths under optimum irrigation

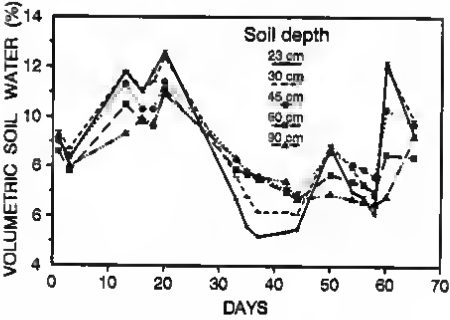


Figure 4 15 Volumetric soil water content at different depths under rainfed conditions

Depth of Water Within 0-90 cm Soil Profile

Depth of water within the root zone was computed by multiplying volumetric soil water content (θ_v) x depth of soil. It could also be expressed as volume of water per unit are of a specified soil depth. Depth of water is therefore a measure of the amount of water contained within a specified soil profile. Figure 4.16 shows depths of water within 0-90 cm soil profile over time. Observed depths of water within 0-90 cm soil profile between May 13 and July 15 never exceeded 10.5 cm. Decrease in depth of water was due to evapotranspiration and/or leaching (drainage) while increase in depth of water could be explained by rainfall and/or irrigation. Based on rainfall and irrigation data between May 13 and July 15, there was a cumulative depth of water of 467 mm. The root zone had an average of 72 and 87 mm of water on May 13 and July 15, respectively. If there were no water losses through evapotranspiration and/or leaching the root zone would have 467 mm of water on July 15, but only 87 mm of water ware present. At an estimated average daily potential evapotranspiration of 5 mm of water (weather data at experimental site), approximately 320 mm of water were lost through ET during this time. About 60 mm of water were therefore leached beyond 90 cm between May 13 amd July 15. It is very likely that any chemical in solution phase moved with the water draining out of the root zone.

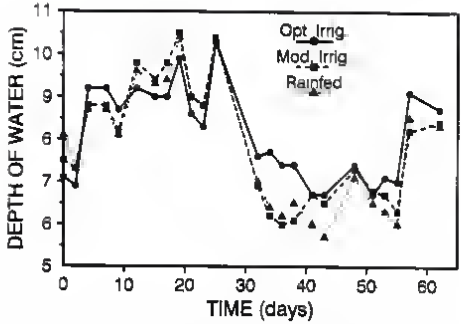


Figura 4.16 Depth of water within 0-90 cm soil profile under rainfed, optimum and moderate irrigations between May 13 and July 15, 1991.

Recovered Chemicals Within the Root Zone

Bromide

Sodium bromide (NaBr) solution was uniformly sprayed on the soil surface in all plots at a rate of 45 kg Br^- ha^{-1} one day after planting. Figure 4.17 shows the average concentration of Br^- with depth over time. Five days after application (DAA) most of the Br^- was within the top 15 cm. This was due to the fact that there was no rainfall and/or irrigation between day of application and first soil sampling. The second soil sampling at 30 DAA showed that less than half of the applied bromide was left within the root zone (0-90 cm). Since Br^- is biologically stable and does not undergo gaseous losses, it is only prudent to conjecture that Br^- not recovered from soil and plants had

leached beyond the root zone Any non adsorbed soluble chemical (e g NO_3) applied to the soil surface has the potential of leaching beyond the root zone Such downward solute movement was achieved with a 7-day cumulative rainfall of 65 mm spread over 17 days No bromide was found within the root zone at 67 DAA High water infiltration and percolation rates of the sandy soil caused the high leaching potential The center of mass of bromide in the soil was not detected because the sampling dates were too far apart and there was heavy rain immediately after bromide application This implies much of the applied NO_3-N also leached beyond the root zone

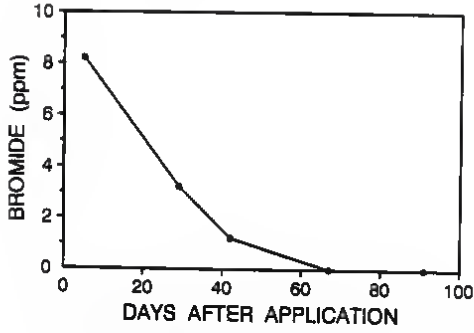


Figure 4 17 Bromide content within 0-90 cm soil depth over time under optimum irrigation

Soil Nitrate N

Two rates of fertilizer N (100 and 300 kg N ha^{-1}) denoted as N_0 and N_1 were applied in three splits of 50 and 150, 25 and 75, and 25 and 75 kg ha^{-1}. First fertilizer split was applied on April 17, whereas second and third splits were applied 8 (April 24) and 50 (June 5) days after initial application (DAA), respectively. The three splits of fertilizer N made tracking of NO_3-N front in the soil difficult. High N and optimum irrigation (N_1W_0) treatment provided the worst leaching scenario in this study.

Soil samplings for NO_3^- extraction were done 14, 38, 50, 75 and 99 days after initial fertilizer application (DAA). The amount of NO_3^- content within a given soil horizon at specific times showed great variability within treatments. Such variability could be attributed to inherent spatial heterogeneity of soil physical properties within the experimental plot and/or uneven distribution of fertilizer during broadcast application (fertilizer in form of granules was broadcast using a manually operated hand held dispenser). Due to the high variability of NO_3-N content within a stratum (0-15 cm, 15-30 cm, 30-45 cm, 45-60 cm, and 60-90 cm) at sampling times, amounts of NO_3-N within the root zone (0-90 cm) were instead computed on each sampling date. This was a better indication of the disappearance of NO_3-N from the root zone. Since NO_3 ions were the only source of applied N in this experiment, the amount of N leached beyond 90 cm could be computed as:

Leached N = (Initial soil N + Applied N) - (Current soil N + Crop N uptake) ... (33)

Figure 4.18 summarizes the amount of NO_3-N within 0-90 cm depth over time for high N input (300 kg ha^{-1}) and optimum irrigation treatment. While 225 kg N ha^{-1}

had been applied before the first soil sampling (May 1), only 103.5 kg N ha^{-1} were recovered from the 0-90 cm soil profile at 14 DAA. A cumulative rain of 101 mm had fallen during this time. Twenty four days later (38 DAA) 44 kg N ha^{-1} were found within the same profile. There had been a cumulative rainfall of 86 cm between the first (14 DAA) and second soil sampling (38 DAA). The sorghum crop was still too young to have substantial N uptake. There was zero NO_3-N content within 0-45 cm soil profile at 75 DAA (Fig. 4.19). Although the third split of NO_3-N was applied on June 5 (50 DAA), there was no NO_3-N within 0-90 cm soil profile at 99 DAA. Since there was zero NO_3-N within 0-90 cm soil depth at harvest, the amount of NO_3-N leached beyond 90 cm can be estimated as

Leached N = (Initial soil N + Applied N) - Crop N content at harvest ..... (34)

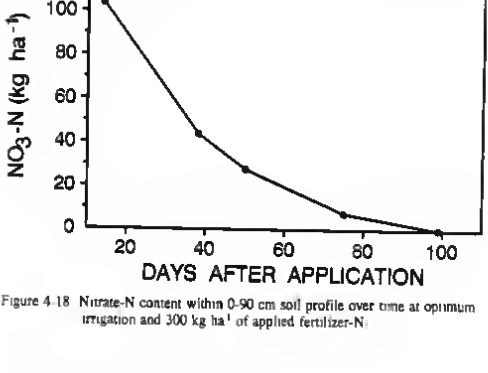


Figure 4.18 Nitrate-N content within 0-90 cm soil profile over time at optimum irrigation and 300 kg ha^{-1} of applied fertilizer-N.

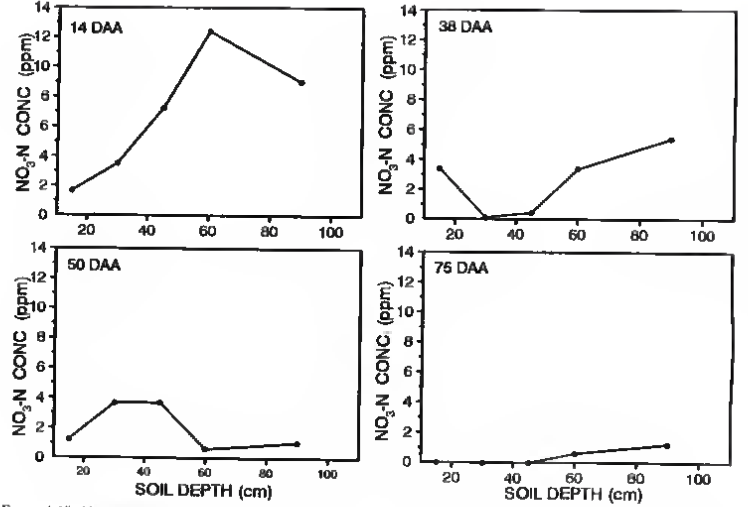


Figure 4.19 Nitrate N concentrations at different soil depths over time under optimum irrigation and 300 kg ha^{-1} applied N

Sorghum seed were not analyzed for N concentration in this study, instead the seeds were assumed to have an average N concentration of 1.5% (Myers and Asher, 1981; Bennett et al., 1990). With an average grain yield of 5318 kg ha^{-1} for treatment N_1W_0, it was estimated that 79.77 kg N ha^{-1} were contained in the sorghum grain. The sorghum crop had a cumulative vegetative (leaf + stem) dry weight 3197 kg ha^{-1} at harvest with an average vegetative N concentration of 0.34% for the same treatment, which translated to 10.87 kg N ha^{-1}. Assuming negligible root N content at harvest (or that root N content was part of recovered soil N), crop N uptake was estimated to be 90.64 kg ha^{-1}. Using Eq. 34, approximately 209 kg ha^{-1} of N leached beyond 90 cm depth in plots applied with 300 kg ha^{-1} of fertilizer N. An estimate of 69% of applied N leached beyond the root zone. The potential proportion of NO_3-N leaching beyond 90 cm could be even higher with the single fertilizer application just before planting.

Presence of Br^- at 90 cm depth is further evidence that some of the applied N had leached beyond the root zone. Amount of water input (rainfall and/or irrigation), properties of N-fertilizer (source of N, formulation, solubility), and physical soil properties (sandy soil) accounted for the high N leaching observed.

Atrazine Adsorption Isotherms

Unlike Br^- and NO_3^- ions, atrazine is subject to adsorption by soil particles. Residual atrazine recovered from soil samples accounted for both soluble and adsorbed quantities. Freundlich linear isotherms showed atrazine adsorption coefficients (K_d) of 0.65, 0.66, 0.29, 0.236, and 0.16 ml g^{-1} for 0-15, 15-30, 30-45, 45-60 and 60-90 cm soil

profiles, respectively (Fig. 4.20). Most of the atrazine was adsorbed within the 30 cm of top soil. It is reasonable to assume that soil organic matter in upper horizons accounted for the high adsorption coefficients observed. Caution must therefore be exercised in interpreting leaching of atrazine to include adsorption and degradation.

Degradation of Atrazine in Soil

Degradation data of atrazine could not adequately be described by one equation. There were two degradation rate coefficients described in two phases, initial and secondary. Initial degradation rate of atrazine within the first 7 days (initial phase) was fast, followed by a slow rate (secondary phase) thereafter. Two first order equations (Hyzak and Zimdahl, 1974, Zimdahl and Gwynn, 1977) were used to describe the two degradation rates. Atrazine had an initial apparent degradation rate coefficient (k_1, day^{-1}) of 0.1095 and 0.1075 for the topsoil and subsoil, respectively (Figs. 4.21 and 4.22). The secondary phase had degradation rate coefficients of 0.0165 and 0.0060 for topsoil and subsoil, respectively (Figs. 4.21 and 4.22). Half lives were calculated using the fitted regression line described by the data points at the time of chemical disappearance. Half lives ($t_{½}$) for the initial degradation phase were computed based on initial degradation rate coefficients using Eq. 28 as follows:

$$M = ½M_0 \text{ at } t_{½} \quad (35)$$

Substituting Eq. 35 into Eq. 28 gives

$$½ = e^{-kt_{½}} \quad (36)$$

$$\ln(½) = -kt_{½} \quad (37)$$

$$t_{½} = (\ln ½)/-k = -0.693147/-k \quad (38)$$

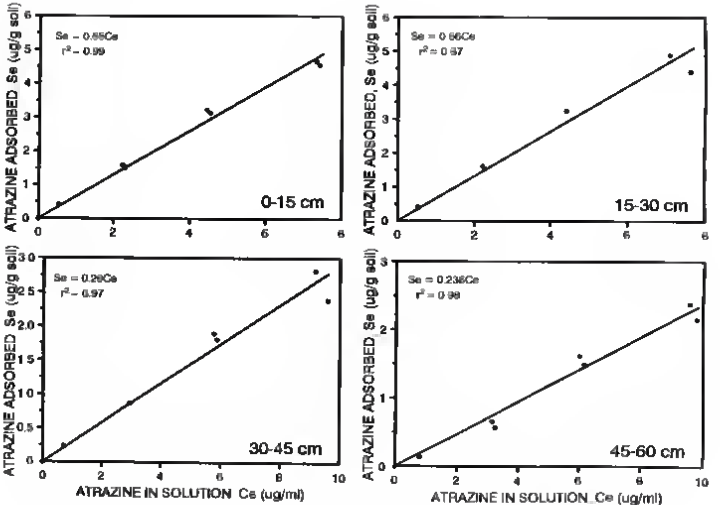


Figure 4.20 Linear adsorption isotherms of atrazine at different depths of a sandy soil cropped with sorghum

Equation 38 cannot be used to calculate half life ($t_{1/2}$) during the second degradation phase. Instead the time which corresponds to ln 0.5 (i.e. -0.693) is the half life.

Estimated half lives under controlled laboratory conditions varied from 6.3 to 32 days in topsoil and 6.4 to 83 days in subsoil, depending on the degradation phase used (Fig. 4.21). It is difficult to measure degradation under field conditions since a lot of the factors affecting degradation fluctuate with time and space. Such factors include soil water content, temperature, microbial population, and sorption. Half lives could even be more variable under such conditions. Short and Enfield (1988) reported half lives between 12 and 238 days in three different soils containing 10 chemicals while Wauchope et al. (1992) found half lives ranging from 12 to 120 days. Variation in half lives in this study could partly be attributed to fluctuation of microbial populations within and between soil horizons. Microbial populations tend to be high in topsoil, hence the observed short half life. It is unfortunate that degradation data obtained from controlled laboratory conditions are usually used to explain processes under field conditions. Degradation data under field conditions remain to be a challenge, besides estimation.

Retardation of Atrazine in Soil

As a result of sorption processes, atrazine moves much more slowly through the soil than the water that is transporting it. This effect is called retardation. Retardation factor, R, is calculated as

$$R = 1 + \frac{\Gamma K_d}{\theta_v} \qquad (39)$$

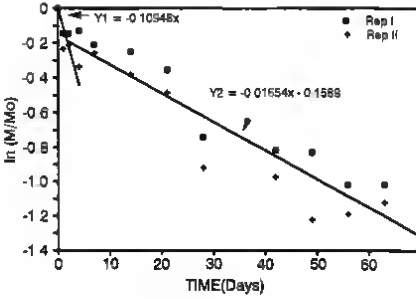


Figure 4.21 Degradation of atrazine in Millhopper topsoil (0-30 cm)

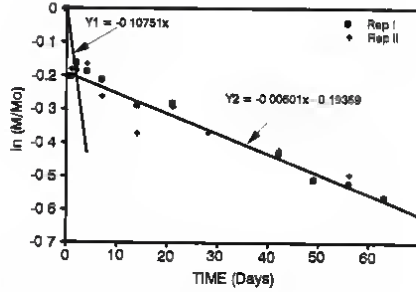


Figure 4.22 Degradation of atrazine in Millhopper subsoil (30-60 cm)

where R is the retardation factor, Γ is the soil bulk density, K_d is the sorption coefficient and θ_w is gravimetric water content. Calculation of retardation factor (R) based on volumetric soil water content θ_v can be derived as follows

$$\theta_v = \frac{V_w}{V_t} \quad (40)$$

where V_w is the volume of water, V_t is total volume of soil (water + solid + air). Gravimetric soil water content θ_w is calculated as

$$\theta_w = \frac{V_w}{M_s} \quad (41)$$

where M_s is the mass of soil. Soil bulk density, Γ is the mass of soil divided by total volume of soil (V_t),

$$\Gamma = \frac{M_s}{V_t} \quad (42)$$

Rearranging Eq. 42,

$$M_s = \Gamma V_t \quad (43)$$

Substituting ΓV_t for M_s in Eq. 41,

$$\theta_w = \frac{V_w}{\Gamma V_t} \quad (44)$$

Dividing volumetric water content by gravimetric water content

$$\frac{\theta_v}{\theta_w} = \frac{(V_w/V_t)}{(V_w/\Gamma V_t)} \quad (45)$$

which simplifies to

$$\frac{\theta_v}{\theta_w} = \Gamma \quad (46)$$

Equation 46 can be rearranged as

$$\theta_v = \theta_w \Gamma \quad (47)$$

Substituting θ_v into Eq 39 gives

$$R = 1 + \frac{\Gamma K_d}{\Gamma \theta_w} \quad (48)$$

which simplifies to

$$R = 1 + \frac{K_d}{\theta_w} \quad (49)$$

The topsoil (0-30 cm) and subsoil (60-90 cm) had adsorption coefficients (K_d) of 0 65 and 0 16 m g^{-1}, respectively Based on Eq 49 the topsoil (0-30 cm) had a retardation factor of 7 5 at gravimetric soil water content (θ_w) of 10% compared to 2 5 for the subsoil (60-90 cm) If the average linear soil water velocity is v_a, the average

velocity of sorbed chemical, v_c, is given by the equation

$$v_c = \frac{v_w}{R} \quad \text{(50)}$$

At 10% gravimetric soil water content, atrazine would move 7.5 and 2.6 times slower than water in the top and subsoil respectively. Factors which would improve adsorption of atrazine in sandy soils, such as incorporation of organic residue, may play an important role in reducing leaching.

Atrazine in Soil

Analyses for soil atrazine residues were done 2, 26, 39, and 63 days after application (DAA). Recovered atrazine accounted for both soluble and adsorbed quantities. Figure 4.23 shows the amount of atrazine recovered from different soil depths over time. An average of 121, 25, 14.8 and 6 ppb of atrazine were recovered from 0-15, 15-30, 30-45, 45-60 and 60-90 cm depths, respectively, 2 days after application. Since there was no rainfall or irrigation between day of atrazine application and first soil sampling (2 DAA), it is very unlikely that any of the applied atrazine could have moved beyond the top 15 cm of soil. Any atrazine recovered from the soil below the top 15 cm must be residual from previous applications. There was a substantial reduction of atrazine content within the top 15 cm of soil for the first 26 DAA, decreasing from 125 to 16 ppb in plots under optimum irrigation. Such a decrease could be attributed to microbial degradation ($t_{\frac{1}{2}} \approx 6.3$ to 32 days), plant uptake and leaching.

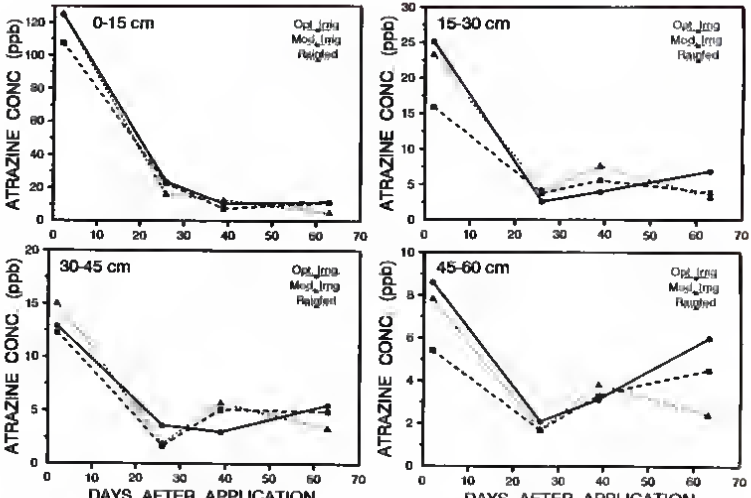


Figure 4.23 Atrazine concentrations at different soil depths over time under three water management regimes

Initial high rate of microbial degradation observed during the first seven days after application supports the rapid disappearance of atrazine from the topsoil. Amount of atrazine absorbed by the crop and weeds was not measured.

An average of 0.44 kg a.i. atrazine ha^{-1} were found within 0-90 cm soil depth two days after application, compared to 1.12 kg a.i. atrazine ha^{-1} applied (Fig. 4.24). Twenty four days later, about 0.10 kg a.i. atrazine ha^{-1} were found within the same soil profile and it remained fairly constant thereafter. This trend was consistent with the degradation study in which the disappearance of atrazine from the soil due to microbial degradation was rapid within the first 7 days ($t_{\frac{1}{2}}$ = 6.3 days). In addition to degradation

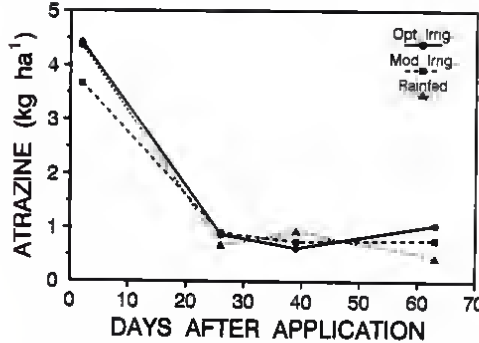


Figure 4.24 Atrazine content within 0-90 cm profile under three water managements

and plant uptake probable miscalibration of the tractor-mounted boomsprayer used to apply atrazine could partly account for some of the observed discrepancy between recovered and applied atrazine within two days after application (with no rainfall) Overall the top soil horizon (0-15 cm) had the highest concentration of atrazine at all sampling dates. Sixty-eight 65.0 and 40 5 % of atrazine recovered within 0-90 cm soil depth at 2, 26 and 39 DAA, respectively, were contained within the top 15 cm suggesting that leaching of atrazine was minimal The relatively higher atrazine content recovered within the top 15 cm of soil compared to subsoil (60-90 cm), could partly be explained by the observed high adsorption coefficients (K_d) for atrazine The top 30 cm of soil profile had an adsorption coefficient (K_d) of 0 65. Water management regimes did not have a significant differential effect ($\alpha = 0\cdot05$) on atrazine movement because of the abundant rainfall which masked the intended irrigation treatments

Despite the fact that a considerable amount of atrazine can be adsorbed to soils with high organic matter or crop residues, leaching could still be a problem with high application rates and/or frequent applications in sandy soils with low organic matter content and low water holding capacity Smith et al (1990) reported that 350 $\mu g\ L^{-1}$ (350 ppm) of atrazine were detected in soil water at a depth of 0·6 m nineteen days after application when atrazine was applied at a rate of 4 5 kg a.i ha^{-1}. Six months after application, 90 $\mu g\ L^{-1}$ were measured in shallow groundwater In a different study in a sandy soil in California, Troiano et al (1990) found atrazine leaching as deep as 3 0 m Although very small quantities of atrazine were detected at 90 cm depth in this study, it is possible that atrazine could accumulate over a period of frequent normal use of the

herbicide. It is very likely that frequent large application rate of atrazine in sandy soils would result in considerable quantities of the herbicide leaching beyond the root zone. Since there is little or no microbial activity at lower soil horizons, it is possible that once atrazine is there it would have a longer persistence, and depending on soil moisture relations, it could accumulate or leach

CHAPTER V

EVALUATION OF SIMULATION MODELS

The Leaching Estimation And Chemistry Model (LEACHM) was used to simulate under field conditions, the amount of water, NO_3 N and atrazine within the rooting zone (0-90 cm) of a sandy soil cropped with sorghum. The CERES-Sorghum model simulated soil N balance, crop N concentration, crop N uptake and growth. Measured and predicted data were compared in both models. Model prediction within plus or minus one standard deviation ($\pm\sigma$) of observed data will be regarded as good, and it will be assumed to be poor if it falls outside plus or minus one standard deviation ($\pm\ \sigma$) of observed data. Exceptions to this rule will be explained as necessary.

5.1 LEACHM.

5.1.1 LEACHW - Water

The water version (LEACHW) of LEACHM was run for 81 days starting May 1. Only simulated volumetric soil water content and depth of water within 0-90 cm depth will be reported and compared with actual measured data. LEACHW input data file is summarized in Table B 1. Both simulated output data and actual field data were plotted against time for comparison.

5.1.1.1 Volumetric soil water content

Figure 5.1 shows predicted and measured volumetric soil water content at 30, 60 and 90 cm depth over time in a field cropped with sorghum at optimum irrigation. Predicted soil water content at 30, 60 and 90 cm depths had similar trends over time. However, predicted soil water content fluctuations for the top 30 cm were more pronounced and peaks came earlier than those of the strata below (60 and 90 cm). Such phenomenon was expected because of the sudden changes in soil moisture status caused by water input (rainfall and/or irrigation) and drying inherent in the upper horizon. Once a thin layer of the topsoil was dry through evapotranspiration or drainage, water from lower horizons could not rise by capillarity due to large pore spaces in the sandy soil. Comparison of predicted and measured soil water content data among the three selected depths over time showed that the top 30 cm soil profile consistently had higher values followed by 60 and 90 cm depths, respectively. LEACHW underpredicted soil water content throughout the growing season. Since there are many factors which could influence the predictive accuracy of a model, it is difficult to point out a specific reason which caused LEACHW to underpredict soil water content. This study was intended for the use of the model and not specifically to identify factors which influence accuracy of model prediction. However, I will suggest some of the probable reasons. Water release curves used in this study were derived from a previous experiment conducted at the same experimental site by Omoko (1989). Hutson and Wagenet (1991) cautioned that estimation of soil hydrological properties such as hydraulic conductivity (K_s) is difficult and it varies with space and time, especially under field conditions. Changing soil

structure growing crop roots, holes (or crevices) in soil and agronomic practices such a cultivation may cause hydraulic conductivity to be even more variable. Water loss through evapotranspiration influences soil water content, hence its estimation as a model input could influence predicted soil water content. To avoid speculation, the above mentioned reasons are only suggestions and not confirmed causes for the underprediction of soil water content observed in LEACHW in this study. Differences between measured and simulated volumetric soil water content were within 3% of absolute volumetric units

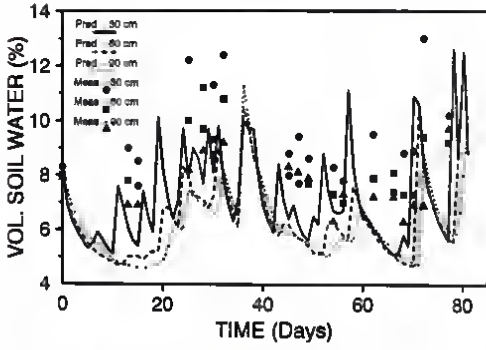


Figure 5.1 Predicted and measured volumetric soil water content at 0-30, 30-60 and 60-90 cm depths starting May 1 through July 15, 1991 as predicted by LEACHW

5.1.1.2. Depth of water

Predicted and observed depths of water are presented in Fig. 5.2. Values of measured depths of water were derived from measured soil water content data by multiplying volumetric water content x soil depth. LEACHW underpredicted the depth of water within 0-90 cm soil profile. Underprediction of depth of water was expected because depth of water is a function of soil water content.

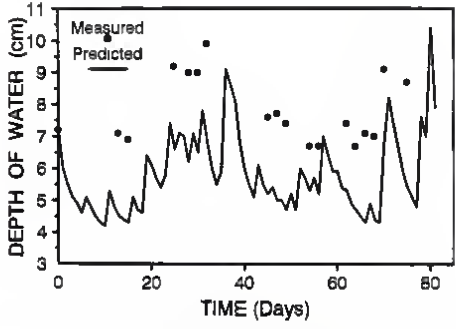


Figure 5.2. Predicted and observed depths of water within 0 - 90 cm soil profile in a field cropped with sorghum under optimum irrigation between May 1 and July 15, 1991 as predicted by LEACHW

5.1.2 LEACHN - Nitrogen

Nitrate-N was the only form of N simulated in this study. LEACHN was set to start simulation on May 1. A total amount of 225 kg ha^{-1} of fertilizer N was already applied to plots recieving high rate of N by April 24 (150 and 75 kg ha^{-1} applied on April 17 and April 24, respectively). Analyses of soil sampled on May 1 from plots applied with high rate of N and optimum irrigation had 103.5 kg NO_3-N ha^{-1} within 0-90 cm depth. The distribution of NO_3-N across the profile was 3.98, 8.74, 17.60, 29.59 and 43.63 kg ha^{-1} at 0-15, 15-30, 30-45, 45-60, and 60-90 cm depth, respectively. No soil samples were taken before May 1; therefore, 103.5 kg NO_3-N ha^{-1} was used as our initial soil NO_3-N content to initialize LEACHN for simulation. A large proportion (42%) of the NO_3-N contained in the root zone on May 1 was within 60-90 cm depth, making it prone to leaching beyond the designated 90 cm lower boundary of the root zone. A third split of 75 kg NO_3-N ha^{-1} was applied on June 4 and it was entered into the LEACHN input file accordingly.

LEACHN overpredicted the amount of NO_3-N contained within the root zone for the first 40 days of simulation (Fig. 5.3). Starting simulation day 60, observed NO_3-N content was very close to zero, whereas LEACHN predicted zero levels starting day 55. Overprediction of NO_3-N content could be due to the underprediction of soil water. Solute movement in the soil is dependent on soil water status, therefore, prediction of solute movement was very much dependent on the underpredicted water content. LEACHN predicted 117 kg NO_3-N ha^{-1} leached beyoed 90 cm depth at harvest compared to computed actual field value of 103 kg NO_3-N ha^{-1} (Fig. 5.4). Approximately 60 kg NO_3-N ha^{-1} were predicted as crop uptake at harvest (Fig. 5.5) compared to computed

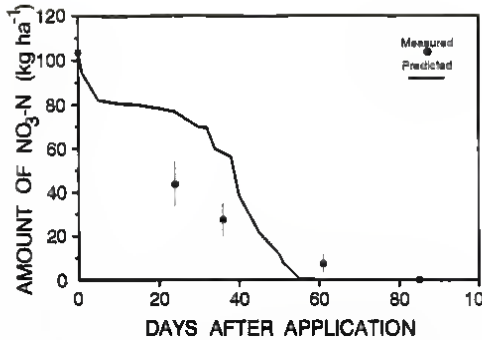


Figure 5 3 Simulated and measured NO_3 N content within 0-90 cm depth between May 1 and July 2 in a field cropped with sorghum under optimum irrigation and 300 kg ha^{-1} of applied NO_3-N, as predicted by LEACHN

actual crop uptake of 75 5 kg N ha^{-1} Predicted crop N uptake was very close to actual data for the first 60 DAP (Fig 5 5) With initial measured soil NO_3-N content of 103 5 kg ha^{-1} on May 1, and additional 75 kg ha^{-1} applied on June 4, a total of 178 5 kg ha^{-1} of applied N was assumed At harvest there was zero N in the root zone, which the model correctly predicted Simulated N leached beyond the root zone (0-90 cm) is shown in Fig 5 4 Amount of leached N was only computed at the end of growing season (harvest) using Eq. 34 because soil N measurements and crop sampling were done at different days during the growing season. For that reason, Fig 5 4 has no accompanying actual field data. In terms of NO_3-N mass balance LEACHN had a total

of 177 kg N ha^{-1} (117 kg N ha^{-1} leached + 60 kg N ha^{-1} crop uptake) at harvest compared with 178 5 kg N ha^{-1} of actual field data (103 5 kg ha^{-1} recovered on May 1 and 75 kg ha^{-1} added on June 4).

Although LEACHN overpredicted soil N content at the beginning of the growing season, simulated soil N content at the end of season (harvest) matched observed data However, since the model was not consistent throughout the simulation period it was overall classified as poor in predicting NO_3-N leached from a sandy soil cropped with sorghum Even though LEACHM has a crop growth subroutine, it is important to note that it is not intended to simulate crop growth per se. The crop growth subroutine can be turned on or off. If LEACHM is to be used in estimating losses of N in advisory situations involving cropped land, then it requires continued development Alternatively, the crop growth subroutine could be substituted or coupled with relevant crop models (e g SOYGRO, CERES-Maize, CERES-Sorghum, SOYGRO) which predict crop N uptake and water absorption much better

5.1.3 LEACHP - Atrazine

The pesticide version (LEACHP) of LEACHM was used to predict the amount of atrazine within 0-30, 30-60, 60-90 and 0-90 cm soil depths over time under field conditions, LEACHP was executed using input data summarized in Appendix Table B.3. Simulation was initiated on May 1, and ran for 62 days. Soil atrazine content at 0-15, 15-30, 30-45, 45-60 and 60-90 cm depths were measured on May 1, May 24, June 6 and July 1 (0, 24, 37 and 61 simulation day). Simulated and measured field data of atrazine at specified soil depths over time are presented in Figs. 5.6 and 5.7

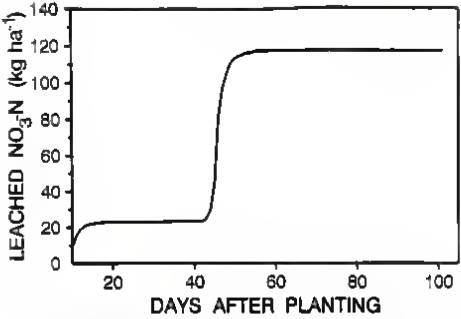


Figure 5.4 Simulated NO_3 N leached beyond 90 cm soil depth between May 1 and July 31 in a field cropped with sorghum under optimum irrigation and 300 kg ha^{-1} of applied NO_3-N, as predicted by LEACHN.

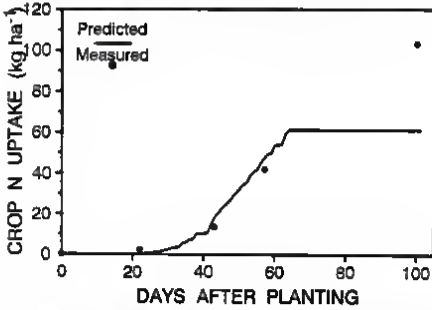


Figure 5.5 Simulated N uptake by sorghum under optimum irrigation and 300 kg ha^{-1} of applied NO_3-N between May 1 and July 31, 1991 as predicted by LEACHN.

The model predicted the highest amount of herbicide to be within 0-30 cm depth, followed by 30-60 and 60-90 cm. This distribution trend was in agreement with the trend of measured field data (Fig. 5.6). Prediction of soil atrazine content within 0-90 cm depth over time was good (Fig. 5.7). Overall, LEACHP was successful in predicting the distribution trend and amount of atrazine within 0-90 cm soil depth despite the inherent spatial variability of soil physical properties.

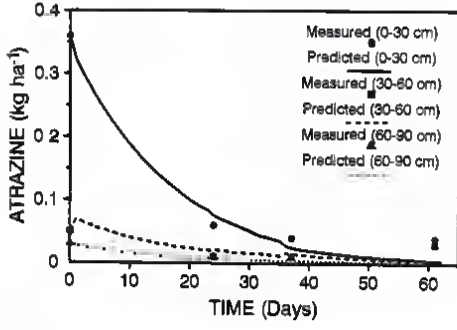


Figure 5.6 Simulated and measured atrazine content at different soil depths in a sorghum field between May 1 and July 2, 1991 as predicted by LEACHP.

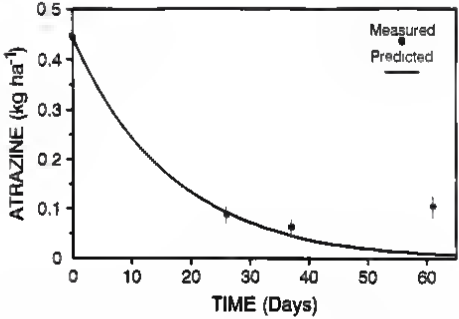


Figure 5 7 Simulated and measured atrazine content within 0-90 cm soil depth in a sorghum field between May 1 and July 2, 1991, as predicted by LEACHP

5.2 CERES-Sorghum model

The CERES-Sorghum model was run under two fertilizer treatments and three water management regimes. Comparisons between simulated and measured data were made on the following: i) phenology (germination, emergence, flowering, physiological maturity), ii) leaf area index, iii) dry matter accumulation (leaf, stem, total), iv) tissue N concentration (leaf, stem, vegetative), v) tissue N accumulation (leaf, stem, vegetative), vi) grain yield and vii) soil N balance

5.2.1 Phenological predictions

Accurate prediction of germination, emergence, flowering and physiological maturity requires accurate weather data, correct adjustment of genetic coefficients (P1 and P2) and estimate of initial soil water content. CERES-Sorghum correctly predicted crop emergence, flowering and physiological maturity within one day of actual field data; however, the coefficients had been calibrated to fit observed dates. Neither N nor water management had an influence on crop development.

5.2.2 Leaf Area Index

Simulated and measured leaf area indices (LAI) for crops receiving 100 and 300 kg N ha^{-1} under optimum irrigation (N_0W_0 and N_1W_0) are shown on Figs. 5.7 and 5.8, respectively. Measured LAI values were consistently increasing at early stages of development until 50 DAP, after which they were erratic. CERES-Sorghum overpredicted LAI during the early growing season (Fig. 5.8 and 5.9). Predicted LAI values were higher than observed during the first 55 days, after which the model under predicted. In both cases the values and trend of predicted and actual data were closer at the early than late stages of crop growth. Predicted maximum LAI values were reached earlier than observed values in both 100 and 300 kg N ha^{-1} (N_0 and N_1) treatments, but they were smaller in magnitude than actual field data. Model prediction was poor, passing through the standard deviation bars of only 20-50% of the sample points.

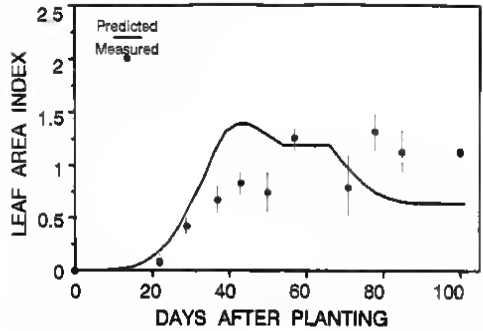


Figure 5 8 Simulated and measured LAI of sorghum under optimum irrigation and 100 kg N ha^{-1} as predicted by CERES Sorghum

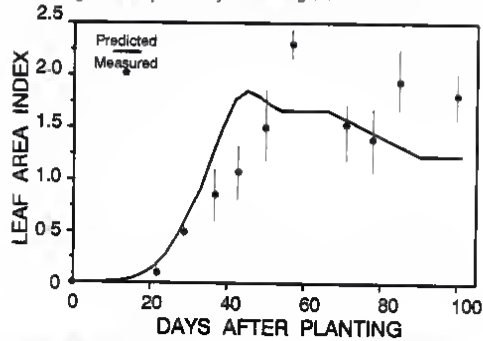


Figure 5 9 Simulated and measured LAI of sorghum under optimum irrigation and 300 kg N ha^{-1} as predicted by CERES-Sorghum

5.2.3 Leaf Dry Weight

Measured and predicted leaf dry weight during the growing season for sorghum crops fertilized with 100 and 300 kg N ha^{-1} and grown under optimum irrigation are shown in Figs 5.10 and 5.11, respectively. CERES-Sorghum slightly over estimated leaf dry weight during the vegetative phase in all treatments. Unusually high rainfall during the season caused most of the applied N to leach, resulting in early leaf senescence due to N deficiency. A better prediction of leaf dry weight was observed just before the onset of reproductive phase (58 DAP) to physiological maturity

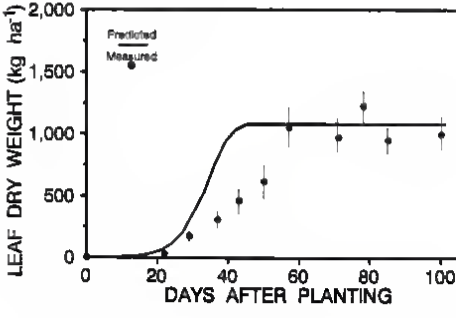


Figure 5.10 Predicted and measured leaf dry weight of sorghum under optimum irrigation and 100 kg N ha^{-1}

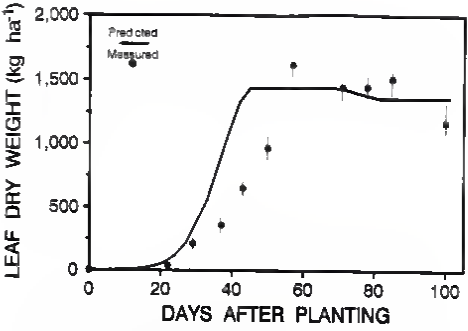


Figure 5.11 Predicted and measured leaf dry weight of sorghum under optimum irrigation and 300 kg N ha^{-1}.

5.2.4 Stem Dry Weight

Predicted and measured stem growth under optimum irrigation and at 100 and 300 kg ha^{-1} of applied N are compared in Figs 5.12 and 5.13, respectively. Simulated stem weights were very close to measured values in both treatments for the first 44 DAP. The treatment receiving optimum irrigation and 100 kg N ha^{-1} was consistently over predicted starting 44 DAP until harvest (Fig. 5.12). In general, predictions under optimum irrigation and 300 kg N ha^{-1} were better than under 100 kg ha^{-1}. Overall, CERES-Sorghum predicted late-season stem growth poorly.

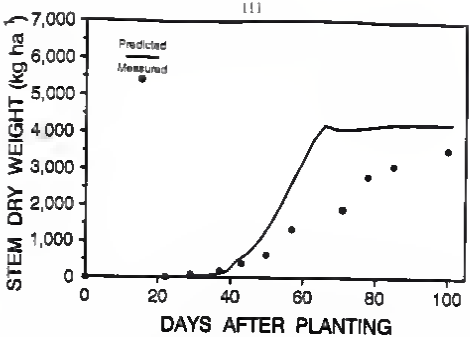


Figure 5 12 Measured and simulated stem dry matter accumulation of sorghum grown with optimum irrigation and 100 kg N ha^{-1}.

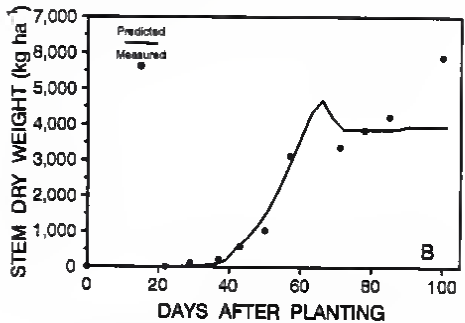


Figure 5 13 Measured and simulated stem dry matter accumulation of sorghum grown with optimum irrigation and 300 kg N ha^{-1}

5.2.5 Aerial Total Dry Matter

Accurate simulation of total above ground biomass is important for accurate prediction of crop nutrient uptake. Figures 5.14 and 5.15 summarize measured and simulated crop aerial dry matter. Predicted and observed TDM were close during the vegetative phase and overpredicted at the onset of reproductive phase to physiological maturity. Overall, CERES-Sorghum model could not correctly predict total aerial dry matter accumulation during the reproductive phase (60-92 DAP).

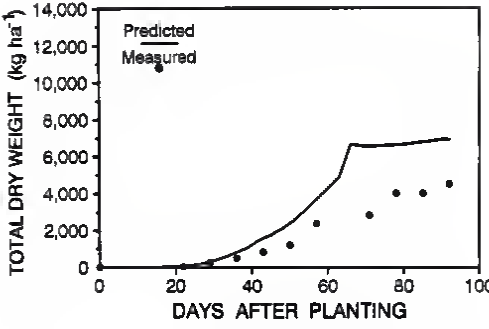


Figure 5.14 Measured and simulated total dry matter accumulation of sorghum grown with optimum irrigation and 100 kg N ha^{-1}

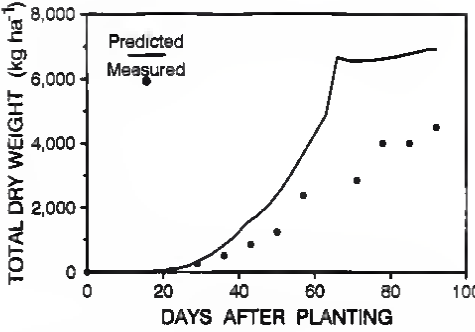


Figure 5.15 Measured and simulated total dry matter accumulation of sorghum with optimum irrigation and 300 kg N ha^{-1}.

5.2.6 Grain Yield at Harvest

Measured and predicted grain yield of sorghum under two water management regimes (optimum irrigation and rainfed) and two rates of fertilizer N application (100 and 300 kg ha^{-1}) are summarized in Table 5.1. Sorghum grain yield predictions were closer to observed field data at high rather than low fertilizer application rate. The CERES-Sorghum model underpredicted grain yield in all treatments. Grain yield in treatments with low N application was underpredicted by more than 50%.

Table 5 1 Measured and predicted grain yield of sorghum at harvest

Treatment		Grain yield	
N rate	Irrigation	Measured	Predicted
kg ha^{-1}		kg ha^{-1}	
100	Optimum	3493	1320
100	Rainfed	3230	1406
300	Optimum	5318	5012
300	Rainfed	4751	3796

5.2.7 Vegetative (leaf + stem) N Concentration

The CERES-Sorghum was fairly consistent and close in predicting vegetative N concentration in all treatments throughout the season. Figures 5 16 and 5 17 summarize predicted and observed vegetative N concentrations of sorghum under optimum irrigation and 100 and 300 kg N ha^{-1}, respectively. Fertilizer-N at a rate of 100 and 300 kg ha^{-1} had no significant effect on the trend and magnitude of predicted and observed vegetative N concentration. Simulated and measured vegetative N concentration were within 1% (in absolute N concentration units)

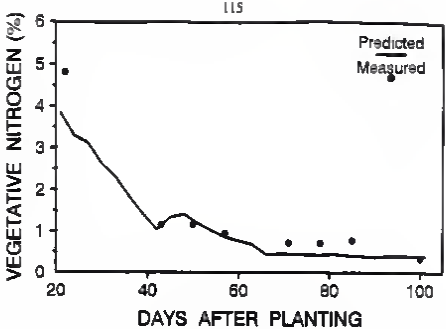


Figure 5.16 Measured and simulated vegetative N concentration of sorghum grown with optimum irrigation and 100 kg N ha^{-1}.

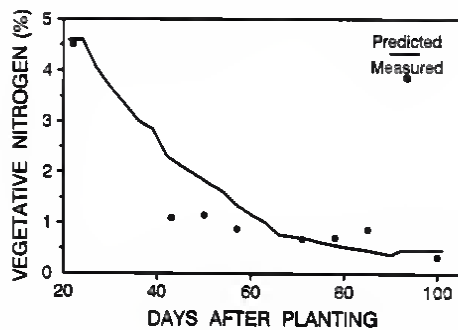


Figure 5.17 Measured and simulated vegetative N concentration of sorghum grown with optimum irrigation and 300 kg N ha^{-1}

5.2.8 Vegetative (leaf + stem) N Accumulation

CERES-Sorghum overpredicted vegetative N content of sorghum in all treatments. Vegetative tissue N decreased during the reproductive phase (starting 60 DAP) indicating that there was mobilization and transfer of N from leaves and stem to reproductive sinks. Rapid increase in N accumulation coincided with the linear crop growth phase (22-55 DAP). In general, the model was poor in predicting vegetative N content (Figs. 5.18 and 5.19).

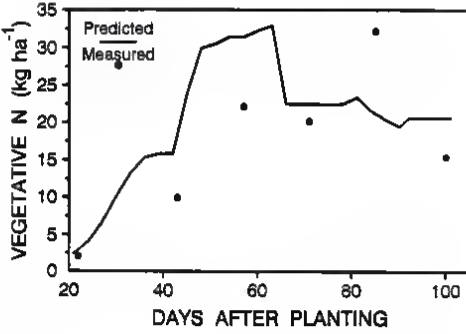


Figure 5.18 Measured and simulated vegetative N accumulation of sorghum under optimum irrigation and 100 kg N ha^{-1}

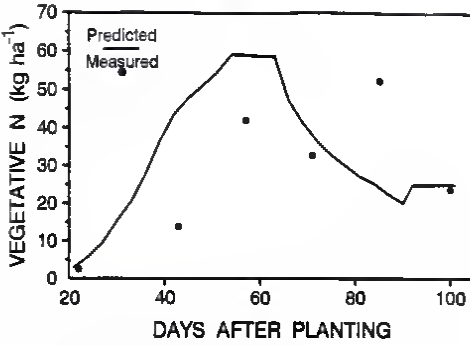


Figure 5 19 Measured and simulated vegetative N accumulation of sorghum under optimum irrigation and 300 kg N ha^{-1}

5.2.9 Crop N Uptake

Measured crop N uptake was a summation of N concentration times dry weight of leaf, stem and seed. Predicted and measured crop N uptake of sorghum under optimum irrigation and two rates of fertilizer N (100 and 300 kg ha^{-1}) are presented in Figs 5 20 and 5 21, respectively. At harvest (100 DAP), CERES Sorghum predicted crop N uptake of 136 kg ha^{-1} in crop under optimum irrigation and 300 kg ha^{-1} of applied fertilizer N, compared to measured N uptake of 90 64 kg ha^{-1}. Under optimum irrigation and 100 kg ha^{-1} applied N, the model predicted crop N uptake of 45 kg ha^{-1} compared with measured crop N uptake of 68 kg ha^{-1}. Prediction of crop N uptake over time was poor in all treatments

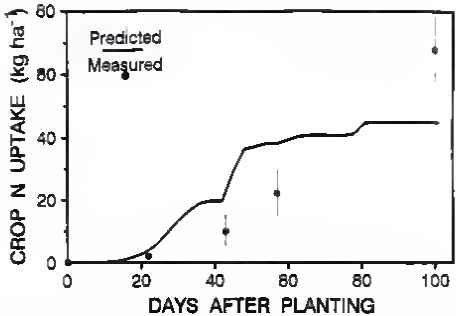


Figure 5 20 Measured and simulated crop N uptake of sorghum under optimum irrigation and 100 kg N ha^{-1}

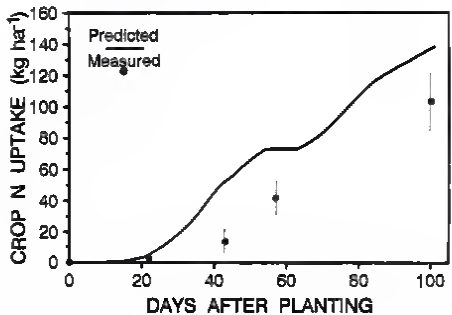


Figure 5 21 Measured and simulated crop N uptake of sorghum under optimum irrigation and 300 kg N ha^{-1}

5.2.10 Leached NO_3-N

Figure 5.22 presents the predicted amount of NO_3-N leached beyond 90 cm soil depth in treatments under optimum irrigation and two fertilizer-N application rates (100 and 300 kg ha^{-1}). At harvest, CERES-Sorghum predicted 67 and 182 kg NO_3-N ha^{-1} leached from the root zone in the low and high fertilizer application rate treatments respectively. Soil samples taken 100 DAP (harvest) had zero NO_3-N content in all treatments. Using Eq. 34, it is approximated that 209 kg N ha^{-1} (300 kg N ha^{-1} applied - 90.64 kg N ha^{-1} crop uptake) leached beyond the root zone at the end of growing season from plots receiving 300 kg N ha^{-1} of fertilizer and optimum irrigation.

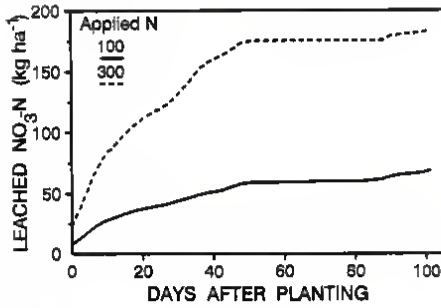


Figure 5.22 Simulated NO_3-N leached beyond 90 cm soil depth in a sorghum field under optimum irrigation and two fertilizer rates (100 and 300 kg N ha^{-1}) between April 16 and July 31, 1991, as predicted by CERES-Sorghum

5.3. Comparison Between LEACHM and CERES-Sorghum

The two models are compared with respect to their basic structure and processes used for water movement, solute transport, crop growth, and crop N uptake. Unlike CERES-Sorghum, LEACHM had a pesticide component.

5.3.1. Water Movement and Solute Transport

LEACHM considers water movement and chemical transport through a soil matrix. The model used numerical solutions of the Richards equations for water flow in unsaturated soils and the convective-dispersive equation (CDE) for chemical transport. Richards equations have been modified by several researchers to accomodate sinks like transpiring plants (or crop). Details of the structure of LEACHM is beyond the scope of this study. CERES-Sorghum uses a "tipping bucket" principle for water and solute movement. The soil profile is divided into small segments (layer). Inorder for water to move from one layer to another, water content of a given layer has to reach saturation, and then it will trickle to the underlying segment. Solute moves with the water.

5.3.2. Crop Growth

CERES-Sorghum is a process oriented mechanistic-deterministic crop growth model. It requires input data for soil, weather and management conditions, and it operates on a daily time step. It uses the input data in different detailed equations which describe processes that influence plant growth and development. Unlike CERES-Sorghum, LEACHM is not intended to simulate crop growth. It uses one or two empirical equations which try to express plant growth in simple terms. LEACHM can be run under three crop growth options, namely i) no plants (crop), ii) plants present

with constant root distribution and crop cover, and ii) a growing crop. The crop growth subroutines are based on simple empirical equations and there is no feedback between soil conditions and plant growth. The crop subroutine shares no variables with the rest of the program (Hutson and Wagenet, 1992) except the CALL statements; therefore it can be replaced with other crop growth programs (models) which are more applicable. In view of the above, when LEACHM is used to simulate water, N or pesticide movement on cropped land with the crop growth subroutine turned on, it would be better to replace or couple it with a relevant crop growth model (e.g., CERES Sorghum).

CERES-Sorghum model is intended to simulate the growth, development and yield of sorghum. In addition to growth, the model simulates N and P balance (crop uptake and leaching), mineralization and immobilization of N associated with crop residues.

5.3.3 Leached NO_3-N and Crop N Uptake

LEACHN, the N version of LEACHM predicted 117 kg NO_3 N ha^{-1} had leached beyond the root zone (90 cm) at the end of the growing season (harvest) compared with 182 kg ha^{-1} predicted by CERES-Sorghum. Simulations of LEACHN were initiated on May 1, fourteen days after fertilizer application, whereas CERES-Sorghum was initiated at fertilizer application (April 17). Thus, direct vale comparisons of N leaching are not proper. CERES Sorghum had a simulated crop N uptake of 136 kg ha^{-1} at physiological maturity in sorghum plots under optimum irrigation and 300 kg ha^{-1} of applied N while LEACHN predicted an uptake of 60 kg N ha^{-1} for the same treatment. CERES-Sorghum predictions were closer to the observed crop N uptake of 103 kg ha^{-1}. Both models predicted crop N uptake poorly.

CHAPTER VI

SENSITIVITY ANALYSIS

Introduction

Sensitivity of a model is a measure of change of an output to a change in a parameter and/or an input (Thornley and Johnson, 1990). A dimensionless measure of sensitivity of prediction of output Y to parameter P_j is

$$S(Y,P_j)=\frac{\partial Y P_j}{\partial P_j Y}=\frac{\delta Y}{Y}\frac{P_j}{\delta P_j} \qquad (51)$$

where δP_j denotes a small finite change in the parameter P_j and δY is the change produced in Y. Parameters could be ranked through sensitivity analysis. Using Eq. 51 parameters with $S(Y, P_j) > 1$ have larger effects on Y and vice versa. Sensitivity analysis may be useful in identifying components of the model which can be simplified without affecting the overall performance of the model. For example, a high value of coefficient of variance (CV) of a parameter means that such a parameter has little effect on the predictions of the model. It may be possible to remove such a parameter from the model but there might also be good reasons (biological, physical or environmental) for retaining the parameter, even though it has little effect on the model's predictive performance (Thornley and Johnson, 1990). Sensitivity analysis can enable modelers and/or users to identify the range of possible management options using models and how

such manipulations are valid in real situations

The objectives of sensitivity analysis in this study are i) to identify a few parameters and agronomic inputs which influence the performance of the model (s) used and ii) illustrate that model predictions should be interpreted within a known range of inputs and parameters Identification of such parameters and inputs might influence the precision and priority of data to be collected

LEACHM and CERES-Sorghum model were used in this study to predict leaching of NO_3-N and atrazine, crop N uptake and crop growth A few inputs and parameters were changed in order to evaluate the sensitivity of the models Inputs and parameters changed in the CERES Sorghum model included weather data, amount of applied N time of N application, single N application versus split application, soil drained upper limit (DUL) of water, lower limit of plant extractable water (LL), and soil water content at saturation (SAT) Water release curve, degradation rate coefficient of atrazine and amount of atrazine applied were changed in LEACHM Sensitivity analyses of the two models were done independently, and their evaluations are not necessarily compared.

CERES Sorghum Model

The CERES-Sorghum model was used to predict crop growth, crop N uptake and leaching of NO_3-N The following inputs were changed as follows, i) weather - 5 years of weather data, ii) amount of N applied 0, 50, 100, 200 300 and 400 kg NO_3-N ha^{-1}, iii) time of N application - one week before planting and at planting iv) one time application of N versus split application (3 splits) Changed soil water parameters were

drained upper limit (DUL), lower limit of plant extractable water (LL), and water content at saturation (SAT). Evaluated outputs included i) N leached beyond the root zone (0-90 cm), ii) crop N uptake, iii) grain yield, iv) maximum leaf area index (LAI), and v) crop biomass at harvest.

Weather

CERES-Sorghum was run using weather data of five years, namely, 1983, 1984, 1985, 1986 and 1987. The crop received 300 kg ha^{-1} of fertilizer N in three splits (150, 75, and 75 kg ha^{-1} applied on April 17, April 24 and June 4, respectively). Planting was done on April 22 in all years. The amount of N leached beyond the root zone (0-90 cm), and crop N uptake for five different years are summarized in Figs. 6.1 and 6.2, respectively. Sorghum grain yield, maximum LAI, and biomass at harvest are presented in Table 6.1.

CERES-Sorghum was sensitive to weather data since the weather components (amount of precipitation, rainfall distribution, solar radiation, temperature, evaporation) vary from one year to another. Sensitivity due to different weather was expected because weather components have an influence on processes such as soil water movement, leaching of nutrients (N), rate of chemical transformation and degradation, crop N uptake, crop growth and development. Model predictions performed in given set of weather conditions are necessarily the same under a different set of weather conditions. Model inputs and parameters should be changed to reflect weather conditions.

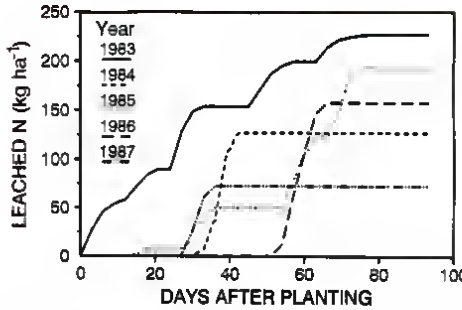


Figure 6.1 Simulated N leached beyond the root zone (0-90 cm) in a sandy soil cropped with sorghum using weather data of five years

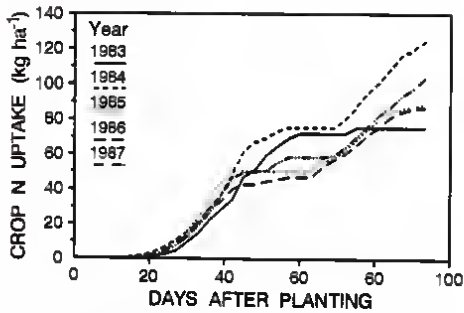


Figure 6.2 Simulated crop N uptake of sorghum grown in a sandy soil using weather data of five years

Table 6.1 Predicted sorghum grain yield, maximum LAI and biomass at harvest using different weather data

Year	Grain yield	Max LAI	Biomass at harvest
	----- kg ha^{-1} -----		----- kg ha^{-1} -----
1983	3455	1 55	9303
1984	5178	1 82	11451
1985	3959	1 26	9058
1986	3769	1 05	8441
1987	3883	1 45	9068

Amount of N Applied

Five fertilizer N treatments were applied at planting using the weather data of 1991. The fertilizer treatments were 0, 50, 100, 200, 300, and 400 kg NO_3-N ha^{-1}. Predicted N leached beyond the root zone and crop N uptake are shown in Figs 6 3 and 6 4, respectively. Table 6 2 summarizes predicted grain yield, maximum LAI and biomass at harvest. The amount of N leached beyond the root zone increased with increasing rate of N application. This was an accurate reflection of what the model was expected to predict. Unlike leached N, crop N uptake increased with increasing N input up to 300 kg ha^{-1} of applied N, but there was no difference in simulated crop N uptake between 300 and 400 kg ha^{-1} of applied N. That means the model was insensitive to N input between 300 and 400 kg ha^{-1} with respect to crop N uptake for the cultivar used. The model was very sensitive to applied N in grain yield and biomass prediction. Maximum LAI did not change with increasing N application between 100 and 400 kg ha^{-1} (Table 6.2)

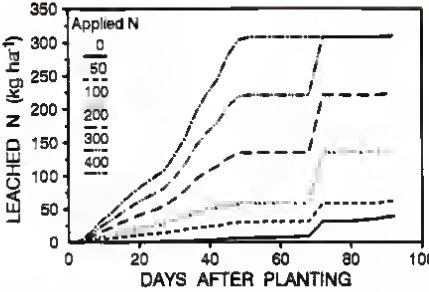


Figure 6 3 Simulated N leached beyond the root zone (0-90 cm) in a sandy soil cropped with sorghum as influenced by different amounts of fertilizer N

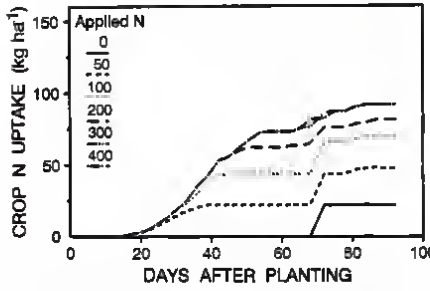


Figure 6 4 Simulated crop N uptake of sorghum as influenced by different amounts of applied fertilizer N

Table 6 2 Predicted sorghum grain yield maximum LAI, and biomass at harvest using different amounts of fertilizer N

Applied N	Grain yield	Max LAI	Biomass at harvest
kg ha^{-1}	----- kg ha^{-1} -----		---- kg ha^{-1} ----
0	0	0 00	17
50	714	1.14	4245
100	1471	1.65	8082
200	3062	1 66	9587
300	3951	1 66	10360
400	4342	1 66	10811

Time of Fertilizer Application

The time of fertilizer application relative to date of planting can have an influence on the amount of N leached, crop N uptake, and crop growth Simulations on the effects of time of fertilizer N application were initiated one week before planting and at planting using 300 kg N ha^{-1} and optimum irrigation Amount of leached N and crop N uptake over time are shown in Figs 6 5 and 6 6 Grain yield, maximum LAI and biomass at harvest are summarized in Table 6 3

The model was sensitive to time of fertilization with respect to N leaching, crop N uptake, grain yield, LAI, and crop biomass at harvest Time of fertilizer application has an interactive effect with weather and crop, therefore, sensitivity should be expected More leached N was simulated when fertilizer was one week before planting than at planting because the fertilizer was subjected to more water input (rain and/or irrigation) in the former than the later

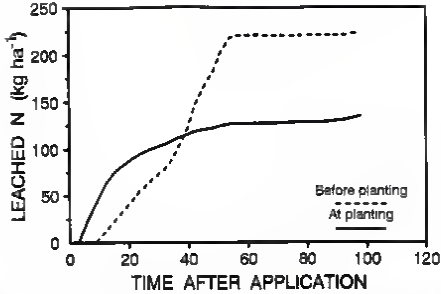


Figure 6 5 Simulated N leached beyond the root zone (0-90 cm) in a sandy soil cropped with sorghum as influenced by time of fertilizer N application, as predicted by CERES Sorghum

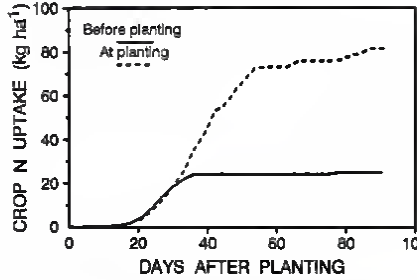


Figure 6 6 Simulated crop N uptake of sorghum grown in a sandy soil influenced by time of fertilizer N application as predicted by CERES-Sorghum

Table 6 3 Predicted sorghum grain yield, maximum LAI, and biomass at harvest by applying 300 kg N ha^{-1} one week before planting and at planting

Time N applied	Grain yield	Max LAI	Biomass at harvest
	----- kg ha^{-1} -----		---- kg ha^{-1} -----
Before planting	823	1 24	4803
At planting	3951	1 66	10360

One Time Application versus Split Application of N

Three hundred kg ha^{-1} of fertilizer N were applied once on April 17 compared with 300 kg N ha^{-1} applied in three splits (150, 75 and 75 kg ha^{-1} applied on April 17, April 24, and June 4, respectively) The crop was planted on April 22, using weather data of 1991 Simulated leached N and crop N uptake are summarized in Figs 6 7 and 6 8, respectively Table 6 4 shows simulated grain yield, LAI and biomass at harvest Less N was leached when fertilizer N was applied in three splits than in one time application because splitting predisposed less N to leaching and distributed it over time for efficient use by the growing crop Based on the amount and distribution of water input, application of fertilizer N over time (splitting) can be an important factor in model prediction Prediction of crop N uptake (Fig 6 8), grain yield, total biomass at harvest and LAI (Table 6 4) were affected by the two methods of fertilizer application Since the model was sensitive to split application of N, predictions of the model do not only depend on the amount of N applied but also how the amount was distributed during the growing season

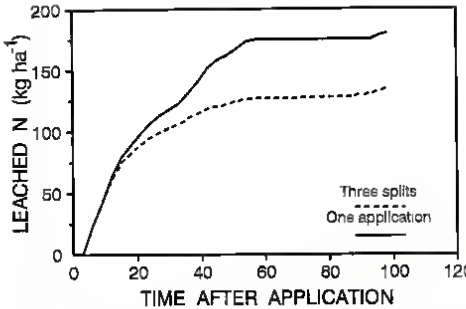


Figure 6.7 Simulated N leached beyond the root zone (0-90 cm) in a sandy soil cropped with sorghum as influenced by one and three split applications of fertilizer N

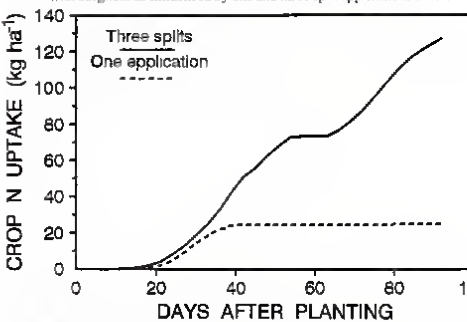


Figure 6.8 Simulated crop N uptake of sorghum grown in a sandy soil as influenced by one and three split applications of fertilizer N

Table 6 4 Predicted sorghum grain yield, maximum LAI, and biomass at harvest using one versus three split applications of 300 kg N ha^{-1}

Method of N application	Grain yield	Max LAI	Biomass at harvest
	kg ha^{-1}		kg ha^{-1}
One application	823	1 24	4803
Split application	5012	1 66	11562

Soil Parameters (DUL, LL, and SAT)

Drained upper limit (DUL), lower limit of plant extractable water (LL), and values of soil water content at saturation (SAT) were changed by a magnitude of ± 20% of the values (standard) used in the field study. The soil type was Millhopper fine sand. Simulations were run using weather data of 1991 and optimum irrigation. Figures 6 9 and 6 10 represent N leached beyond the root zone and crop N uptake, respectively. The model was sensitive to DUL, LL and SAT in predicting N leached (Fig 6 9), but less sensitive in predicting crop N uptake (Fig 6 10). Soil with low (- 20%) DUL, LL, and SAT had the highest amount of N leached because it holds less water at saturation and vice versa. Table 6.5 summarizes the changes of grain yield, maximum LAI and crop biomass at harvest due to ± 20% change in DUL, LL, and SAT. Twenty percent decrease in DUL, LL and SAT decreased sorghum grain and biomass at harvest by 6 6 and 3 4%, respectively, but 20 % increase had no effect.

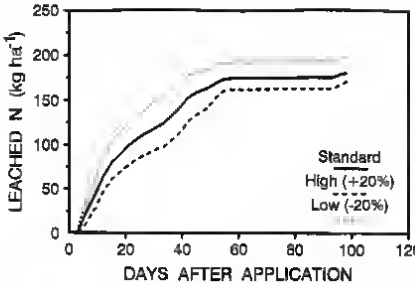


Figure 6.9 Simulated N leached beyond the root zone (0-90 cm) in a sandy soil cropped with sorghum as influenced by soil parameters (DUL, LL, and SAT)

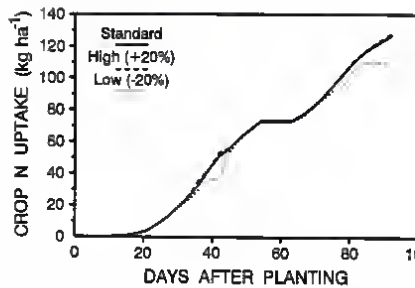


Figure 6.10 Simulated crop N uptake of sorghum grown in a sandy soil as influenced by soil parameters (DUL, LL, and SAT).

Table 6 5 Predicted sorghum grain yield, maximum LAI, and biomass at harvest using different DUL, LL and SAT

Soil parameters	Grain yield	Max. LAI	Biomass at harvest
DUL, LL, SAT	kg ha^{-1}		kg ha^{-1}
Standard	5012	1 66	11562
- 20% change	4683	1 64	11158
+ 20% change	5023	1 66	11576

LEACHM

Athough LEACHM was used to simulate soil water status (content) leaching of N leaching of atrazine, and crop N uptake, sensitivity analyses were performed on only a few inputs and parameters

Degradation Rate Coefficeat of Atrazine

The degradation rate coefficient of atrazine was decreased by two (÷ 2) and three folds (÷ 3) relative to the rate (÷ 1) used in my field study LEACHP was run using weather data of 1991 Simulation outputs of amount of atrazine within 0-90 cm soil depth over time are shown in Fig 6 11 The model was sensitive to degradation rate of atrazine In many instances, modelers and/or users estimate rates of degradation of pesticides without conducting degradation studies under the condition in which the model is being tested It is obvious from Fig 6 11, that the amount of atrazine predicted could vary substantially and solely based on the rate of degradation

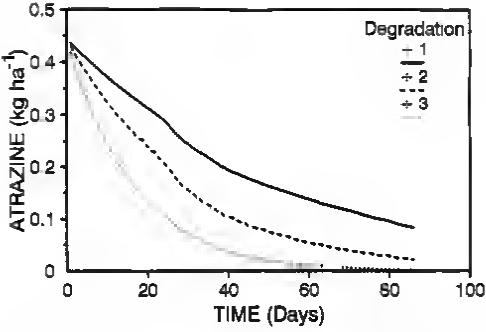


Figure 6.11 Simulated soil atrazine content within the root zone (0-90 cm) in a sandy soil cropped with sorghum using three different degradation rate coefficients

Amount of Atrazine Applied

Sensitivity analyses were performed using 0.44, 0.88 and 1.32 kg a.i. ha^{-1} (x 1, x 2, and x 3, respectively) of atrazine as our initial application rates. All three simulation runs used weather data of 1991. Figure 6.12 summarizes the predicted amount of atrazine within 0-90 cm soil depth over time. The simulated trends and amounts of atrazine in the soil over time were in agreement with theoretical expectations. LEACHP was sensitive to very small changes of atrazine application.

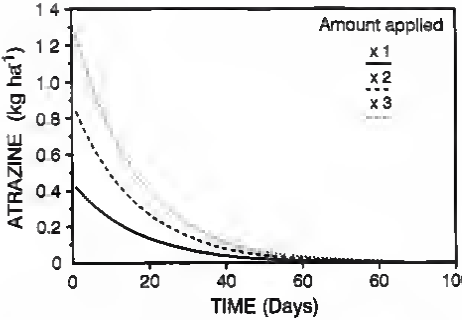


Figure 6.12 Simulated soil atrazine content within the root zone (0-90 cm) in a sandy soil cropped with sorghum using three different application rates

Conclusion

Both CERES-Sorghum and LEACHM were sensitive to a variety inputs and/or parameters within a given range Inputs and parameters to be used in simulation models should be representative of the actual conditions or practices under which the models are intended For example it would be unwise to predict leaching of N in sandy soils using soil parameters of a clay soil However, uses of a model might differ depending on the objectives of the user A model could be adequate to one user but inadequate to another Perhaps it is worth mentioning that precise simulation of all the detailed processes in a profile scale model like LEACHM or CERES-Sorghum is difficult if not impossible On

the other hand, unexplained differences between simulation and measurements advance knowledge because they challenge our current assumptions and prompt new directions for research.

CHAPTER VII

SUMMARY AND CONCLUSION

A field study was conducted to quantify and characterize the amount and movement of NO_3-N and atrazine with respect to water management in a sandy soil cropped with sorghum. A 2 x 3 factorial design in four randomized complete blocks was used. Two levels of N (100 and 300 kg NO_3-N ha^{-1}) in three splits (50, 25, 25, and 150, 75, 75 kg N ha^{-1}) and three water management regimes (optimum irrigation, moderate irrigation and rainfed) composed the treatment combinations. Bromide was applied at a rate of 45 kg ha^{-1} as a tracer for water and NO_3-N movement in all plots. A uniform application of atrazine at a rate of 1.12 kg a.i. ha^{-1} (1 lb $acre^{-1}$) was applied in all treatment combinations as a post-emergence herbicide.

Soil water content was measured during the growing season using a neutron probe. Measurements were taken at 23, 30, 45, 60, and 90 cm depths. Soil samples were collected over time at 0-15, 15-30, 30-45, 45-60, and 60-90 cm depths and analyzed for nitrate, bromide and atrazine.

Part two of the study involved the use of computer simulation models to predict soil water content, NO_3-N and atrazine content at various soil depths within 0-90 cm, amount of NO_3-N leaching beyond 90 cm, crop N uptake, and crop growth. LEACHM and CERES-Sorghum model were used for predictions and model outputs were compared with measured field data.

Despite heavy rainfall during the growing season, measurements showed that volumetric water content in all horizons did not exceed 13% in all treatments. There was a cumulative rainfall and irrigation of 395 mm between May 1 and July 15, with initial depth of water of 72 mm in the 0-90 cm soil profile. The root zone had a water depth of 87 mm on July 15, and estimated cumulative ET of 320 mm between May 13 and July 15. It was estimated that 60 mm of water drained beyond 90 cm soil depth between May 13 and July 15. It is very likely that chemicals in the solution phase leached with the water leaving the root zone.

The first two splits of fertilizer N were applied on April 17 and April 24 respectively. Measurements of soil NO_3-N content within 0-90 cm showed great variability within N treatments on any given sampling date. Such variability could possibly be explained by spatial heterogeneity of soil physical properties (lateral and vertical) and/or uneven distribution of fertilizer during broadcast application. Statistical analyses revealed that water management treatments did not have a significant ($\alpha \leq 0.05$) differential influence on soil NO_3-N content within a given fertilizer application rate. This was mainly due to the fact that heavy rains during the season masked the two irrigation treatments (moderate and optimum irrigation). Fertilizer rates were therefore averaged over irrigation treatments in order to characterize N content across the soil profile. Treatment receiving 300 kg NO_3-N ha^{-1} and optimum irrigation represented the worst leaching scenario, hence discussed here. Over time 104, 44, 30, 9 and 0 kg N ha^{-1} were recovered from 0-90 cm zone at 14, 38, 47, 77 and 100 days after application (DAA), respectively. At harvest (100 DAP), 209 kg NO_3-N ha^{-1} had leached beyond the

root zone, approximately 69% of the applied N. Crop N uptake was estimated to be 90.64 kg ha^{-1}. Nitrate-N moved quickly through the soil profile because it was not adsorbed to soil particles. Bromide disappeared from the root zone quickly, decreasing from 8.3 ppm at 9 DAA to 0 ppm at 67 DAA. This was an indication that water and N were leaching beyond the root zone. Crop yellowing was another evident sign of soil N deficiency caused by leaching.

Soil atrazine concentrations within 0-90 cm depth were measured at 2, 26, 39 and 63 DAA. There was a rapid disappearance of atrazine from the topsoil (0-30 cm) due to microbial degradation. Topsoil (0-30 cm) and subsoil (30-90) had half lives of 6.3 to 32 and 6.4 to 83 days, respectively. Fertilizer application rate did not have a significant ($\alpha \leq 0.05$) effect on soil atrazine content, therefore, water treatments were averaged over fertilizer rates. A large proportion of the recovered atrazine was found within 15 cm of the top soil and decreased with increasing depth. This trend was supported by atrazine adsorption coefficient (K_d) values of 0.65, 0.66, 0.29, 0.23 and 0.18 measured at 0-15, 15-30, 30-45, 45-60 and 60-90 cm soil depths, respectively. Retardation factor of 7.5 (at 10% gravimetric soil water content) for atrazine in the topsoil further supported the slow movement of the herbicide in that horizon. Higher adsorption coefficients were expected in the topsoil since adsorption is dependent on soil organic matter content. Two days after atrazine application, an average of 121, 25, 14, 8, and 6 ppb were extracted from 0-15, 15-30, 30-45, 45-60, and 60-90 cm soil depths respectively. These quantities accounted for both adsorbed and non-adsorbed atrazine. Although atrazine was adsorbed by soil particles, the herbicide was detected at all depths

sampled (0-90 cm). At the application rate of 1.12 kg a.i. ha^{-1} (1 lb $acre^{-1}$), only a very small proportion of applied atrazine was detected below 30 cm soil depth. However, it is likely larger amounts of atrazine could leach to lower soil horizons if frequent and higher application rates are used. Soil organic matter of topsoil is a deterrent against leaching of atrazine because of atrazine adsorption to organic matter. Any agronomic practice which involves use and incorporation of crop and/or animal residues in the topsoil should be encouraged.

LEACHW, the water version of LEACHM, underpredicted volumetric soil water content. The difference between measured and estimated volumetric soil water content at different depths in the root zone were up to 3.5% of absolute volumetric units. The top 30 cm of the soil profile was the wettest followed by the 30-60 and 60-90 cm zones. LEACHW predicted this wetting pattern correctly. Likewise, the cumulative depth of water in the same soil profile was poorly predicted. LEACHN overpredicted the amount of NO_3-N in the root zone during the first 50 DAP, after which simulated and measured N were very close. Measured and simulated soil NO_3-N content at 85 DAP were zero. LEACHN predicted 117 kg NO_3-N ha^{-1} had leached beyond the root zone by the end of the growing season from plots under optimum irrigation and 300 kg ha^{-1} of applied N. LEACHN predicted crop N uptake of 60 kg ha^{-1} from treatments of 300 kg ha^{-1} of applied N x optimum irrigation, compared with observed N uptake of 103 kg ha^{-1}. The amount of atrazine recovered from the soil was very minute. However, model prediction of soil atrazine content within 0-90 cm by LEACHP was good. LEACHP correctly predicted the distribution trend of atrazine across the soil profile.

The CERES-Sorghum model predicted crop N uptake of 136 at harvest for a sorghum crop under optimum irrigation and 300 kg ha^{-1} of applied N. The crop receiving 100 kg ha^{-1} of applied N and optimum irrigation had simulated crop N uptake of 45 kg ha^{-1}. The same treatments had 182 and 67 kg ha^{-1} as leached NO_3-N respectively. Measured crop N uptake were 103 and 68 kg ha^{-1} for 300 and 100 kg ha^{-1} of applied fertilizer N. Prediction of crop N uptake by CERES-Sorghum was generally poor in all treatments. Although CERES-Sorghum is intended to simulate crop growth, development and final seed yield, model predictions were poor. Inadequate prediction could be attributed to the model being unable to interpret the processes influencing crop growth and development, inaccurate estimation of crop genetic coefficients and soil parameters, and poor representative crop growth samples (due to uneven stand in some plots).

Sensitivity analysis revealed that CERES-Sorghum was sensitive to weather data, amount of N applied, time of N application, split application of N, and some soil parameters (DUL, LL, and SAT). LEACHM was sensitive to degradation rate coefficient of atrazine and amount of atrazine applied. While many more parameters and inputs could be tested for sensitivity, only a few were tried.

Both of the two models used (LEACHM and CERES-Sorghum) have a soil and crop component. Neither model predicted the soil component (N and water movement) and/or crop component (crop growth, crop N uptake) satisfactorily. While LEACHM might be more rigorous on soil water and solute transport, CERES-Sorghum might be strong in defining crop growth and development. Since the soil and crop components

interact as one system, coupling or substituting the crop growth subroutine of LEACHM with CERES-Sorghum (crop growth crop N and water uptake) could improve the predictive accuracy of the two models This is an exercise worth trying in future studies

CHAPTER VIII

RECOMMENDATIONS FOR FUTURE STUDIES

Studies involving use of biophysical models require a lot of data, of which some are difficult to measure and/or vary with time. Spatial variability of soil physical properties within the area of interest could pose a special problem in data collection and analysis. Therefore, before one embarks on an expensive and time-consuming data collection project, caution should be exercised as to which parameters are sensitive in the model(s) to be used because in some cases just an intelligent estimation of a parameter(s) is adequate. Use of secondary information from previous related studies could also be helpful.

Movement of agrichemicals (fertilizers and pesticides) is dependent on water movement. Accurate prediction of soil water status and movement is dependent on correct measurements and characterization of soil physical properties. Due to inherent spatial variability in soils, physical properties like bulk density, hydraulic conductivity, particle size distribution, and organic matter content are prone to change over time, particularly in a large area under agricultural production. Soil core samples to characterize the soil physical properties should be taken from different locations and depths in the study area, prior to and during the growing season. Soil water content or potential change constantly depending on water input (rainfall and/or irrigation) and water output (drainage, absorption by plants, evapotranspiration). Measurements of soil water

status taken frequently might give a better estimation of water movement than many observations taken sporadically. With limited resources, it would be better to take a few samples on a frequent basis rather than many samples taken infrequently. Change in soil water status might be small or large, therefore it is important for instruments used to be able to detect small changes in soil water content or potential since water flux is a function of such small changes. Transducer-equipped tensiometers and a data logger can detect instantaneous small changes of soil water potential over time and store it.

Often times we intend to assume we have a uniform application of agricultural chemicals on our experimental plots. On the contrary, the application of agricultural chemicals on croplands is not as uniform as intended, especially when the chemical is in granular or pellet form. Higher or lower application rates could also occur due to wrong calibration of application equipment (e.g. sprayer, hopper, etc.) and/or varying ground speed during application. Such discrepancies could show up during data collection or analysis. Uneven distribution of organic mater within the top soil may have an influence on chemicals whose adsorption and movement is a function of soil organic matter content. In a cultivated field where the top soil may be disturbed from time to time through agronomic practices like mechanical weeding, the physical properties of the top soil which influence water infiltration and movement might be altered during the season. However, accurate measurement and careful application rates of agrichemicals should always be observed. Degradation and transformation studies of chemicals done under laboratory conditions might not represent the ever changing conditions in the field. Such degradation and transformation rates should be used with an open mind.

Coupling of soil models which characterize water and chemical (fertilizers and pesticides) movement with crop growth models which predict growth, water and nutrient uptake might be a better approach in evaluating the fate of agrichemicals in cropped fields. Interpretation of model prediction under field conditions should reflect, at an appropriate scale, the intended objectives. Models intended to be used under field conditions describe processes under broad and varying conditions using several equations. Precise simulation under such varying conditions is difficult to achieve. Do not be carried away by small differences between predicted and measured data to overshadow your objective(s) or common sense. Modeling and use of models is a viable and alternative scientific approach to problem solving in agricultural research and production, now and in the future.

REFERENCES

Addiscott, T M and A P Whitmore 1991 Simulation of solute leaching in soils of differing permeabilities Soil Use and Management 7 94-102

Addiscott, T M , and R J Wagenet 1985 Concepts of solute leaching in soils A review of modelling approaches J Soil Sci , 36 411-424

Aldrich, S R 1980 Nitrogen in relation to food, environment, and energy Illinois Agric Exp Sta Special Publ 61 Urbana pp 1-452

Andersen, W P 1983 Weed Science Principles Second Edition West Publishing Company, 655p

Anderson J R 1974 Simulation Methodology and application in agricultural economics Review of Marketing and Agricultural Economics 42 3-36

Anderson, B S 1987 Public Health and Risk Considerations In Toxic organic chemicals in Hawaii's water resources P S C Rao and R E Green (eds.) Research Extension series 086 630 US ISSN 0271 9916

Army, T J 1988 ARS strategic groundwater plan 1 Pesticides USDA-ARS, Washington, DC

Bailey, N T J 1964 The Elements of Stochastic Processes John Wiley New York

Baker J L , J M Laflen, and H P Johnson 1978 Effects of tillage systems on runoff losses of pesticides, a rainfall simulation study Trans Am Soc Agric Eng 21 886-892

Begg, J E , and N C Turner 1976 Crop water deficits Adv Agron 28 161 217

Bennett, J M , J W Jones, B Zur and L C Hammond 1986 Interactive effects of nitrogen and water stresses on water relations of field-grown corn leaves Agron J , 78 273 280

Bennett, W.F., B. B. Tucker, and A.B. Maunder. 1990. Modern Grain Sorghum Production. Iowa State University Press, Ames. 169 p.

Bergstrom, L. and N.J. Jarvis. 1991. Prediction of nitrate leaching from arable land under different fertilization intensities using the SOIL-SOILN models. Soil Use and Management 7:79-84.

Bergstrom, L., A. McGibbon, S. Day and M. Snel. 1991. Leaching potential and decomposition of clopyralid in Swedish soils under field conditions. Environmental Toxicology and Chemistry, 10:563-571.

Boote, K.J., J.W. Jones, J.W. Mishoe and G.G. Wilkerson. 1986. Modeling growth and yield of groundnut. In: Agrometeorology of groundnut. pp. 243-254. Proc. of an International Symposium, 21-26 Aug. 1985. ICRISAT Sahelian Center, Niamey, Niger. Patancheru, A.P. 502 324, India: International Crop Research Institute for Semi-Arid Tropics.

Bowen, W.T., J.W. Jones, R.J. Carsky, and J.D. Quintana. 1993. Evaluation of the nitrogen submodel of CERES-Maize following legume green manure incorporation. Agron. J.

Brady, N.C. 1990. The Nature and Properties of Soils. MacMillan Publishing Company. 866 Third Avenue, New York, New York 10022. Tenth Edition.

Bresler, E. 1973. Simultaneous transport of solutes and water under transient unsaturated flow conditions. Water Resour. Res. 9:975-986.

Bresler, E., and A. Laufer. 1974. Simulation of nitrate movement in soils under transient unsaturated flow conditions. Israel J. Agric. Res. 23:141-153.

Bresler, E., H. Bielorai, and A. Laufer. 1979. Field test of solution flow models in a heterogeneous irrigated cropped soil. Water Resour. Res. 15:645-652.

Burk, T. 1986. Growth and yield model validation: Have you ever met one you liked? Proc. of a computer conference and third annual meeting of the Forest Resources Systems Institute. S. Allen and T.M. Cooney (eds). pp. 35-39.

Byrne, G.F. 1971. An improved soil water flux sensor. Agric. Meteorol. 9:101-104.

Byrne, G.F., J.E. Drummond, and C.W. Rose. 1967. A sensor for water flux in soil: "Point source" instrument. Water Resour. Res. 3:1073-1078.

Byrne, G.F., J.E. Drummond, and C.W. Rose. 1968. A sensor for water flux in soil: 2. "Line source" instrument. Water Resour. Res. 4:607-611.

Calhoun, F G , V C Carlisle, R E Caldwell, L W Zelazny, L C Hammond and H L. Breland 1974. Characterization data for selected Florida soils. Soil Sci. Dept.Res Report SLS 74-1, University of Florida. 293 p

Camp, R.S. and R B Campbell. 1988. Scheduling irrigation for corn in the Southeast USDA, Agr. Res. Ser. ARS-65. 180 p.

Campbell, G. 1974. A simple method for determining unsaturated conductivity from moisture retention data. Soil Sci. 117:311-314.

Carsel, R F., C N. Smith, L A. Mulkey, J D. Dean and P P. Jowise. 1984. User s manual for the pesticide root zone model (PRZM) release 1. EPA-600/3-84-109. Athens GA: U S. EPA

Carter, C E. 1977. Hazardous waste survey for the state of Florida. Prepared for the Florida Department of Environmental Regulation.

Cary, J.W. 1968. An instrument for in situ measurements of soil moisture flow and suction. Soil Sci. Soc. Am. Proc. 32:3-5.

Chiang, C L. 1980. An Introduction to Stochastic Processes and Their Applications. Krieger: Huntington, N Y.

Clarke, R T. 1973. A review of some mathematical models used in hydrology, with observations on their calibration and use. Journal of Hydrology 19:1-20.

Cohen, S Z., S M. Creeger, R F. Carsel and C G. Enfield. 1984. Potential for pesticide contamination of groundwater resulting from agricultural uses. p. 297-325. In: R F. Krueger and J.N. Seiber (eds). Treatment and Disposal of Pesticide Wastes. ACS Symp. Series No. 259, American Chemical Society, Washington, DC.

Cohen, S Z., C. Eiden, and M N. Lorber. 1986. Monitoring groundwater for pesticides in the U S A. p. 170-196. In: R F. Kruger and H N. Nigg (ed.) Evaluation of pesticides in groundwater, ACS Symposium Proc. No. 315, Miami Beach, FL 26 April-3 May 1985. ACS, Washington, DC.

Conover, C S., J J. Geraghty, and G G. Parker Sr.. 1984. "Ground Water". In: Water Resources Atlas of Florida, E A. Fernald and D J. Patton, eds. Tallahassee: Institute of Science and Public Affairs.

Dashman, T., and Stotzky. 1986. Microbial utilization of of amino acids and a peptide bound on homoionic montmorillonite and kaolinite. Soil Biol. Biochem. 18:5-14.

Darcy, H. 1856. Les fountaines publique de Ville de Dijon. Dalmount, Paris.

Davidson J M , P S C Rao, and P. Nkedi-Kizza 1983 Physical Processes influencing Water and Solute Transport in Soils Florida Agric Exp Stn J Series No 4322

Davidson J M , D A Graetz P S C Rao and H M Selim 1978 Simulation of nitrogen movement transformation and uptake in plant root zone Ecological Research Series EPA-600/3-78-029 USEPA, Athens, Georgia

Decision Support System for Agrotechnology Transfer (DSSAT) User s Guide Version 2 1 1989 The International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) IBSNAT Project, Department of Agronomy and Soil Science University of Hawaii, Honolulu, HI 96822

Deeb B S and K W Sloan 1975 Nitrates, nitrites and health Illinois Agric Sta Bull 750

Delwiche C C and B A Bryan 1976 Denitrification Annu Rev Microbiol 30 241-262

Dent, J P , and M J Blackie 1979 Systems Simulation in Agriculture Applied Science Publishers Ltd , Ripple Road, Barking, Essex, England

Dionex Corporation 1987 Ion Chromatography Cookbook A Practical Guide to Quantitative Analysis by Ion Chromatography 1228 Titan Way, P O Box 3603 Sunnyvale, CA 94088-3603

Dirksen, C 1972 A versatile soil water flux meter p 425-442 In Proc 2nd Symp on Fundamentals of Transport Phenomena in Porous Media, Vol, 2 IAHR, ISSS Guelph, Ontario, Canada.

Dirksen, C 1974 Field test of soil water flux meters Trans ASAE 17 1038-1042

Doggett, H 1988 Sorghum Longman Scientific Technical Second edition 512 p

Donigan A S., Jr and N H Crawford. 1976 Modelling pesticides and nitrients in agricultural lands EPA-600/2-76-043 USEPA, Athens, Georgia

Donigian, A S , Jr and P S C Rao 1986a Overview of terrestrial processes and modeling In Hern, S C , and S M Melancon (Eds) Vadose Zone Modeling of Organic Pollutants Lewis Publishers, Inc Chelsea MI pp 3 35

Donigian A S , Jr and P S C Rao 1986b Example model testing studies In Hern, S C , and S M Melancon (Eds) Vadose Zone Modeling of Organic Pollutants Lewis Publishers, Inc Chelsea MI pp 103-131

Ehteshami, M., R C Peralta, H Eisele, H Deer, and T Tindall 1991 Assessing Pesticide Contamination to Groundwater A Rapid Approach Ground Water 29 862 868

Endelman, F J , D R Keeney, T J Gilmour and P G Saffigna 1974 Nitrate and chloride movement in the Plainfield loamy sandy under extensive irrigation J Environ Qual 3 295 298

Enfield, C G , R F Carsel S Z Cohen, T Phan and D M Walters 1982 Approximating pollutant transport to groundwater Groundwater 20 711-722

Erickson, L.E , andK H Lee 1989 Degradation of atrazine and related s-triazines Critical Reviews in Environmental Control 19 1-14

Fan, L T , J R Too and R Nassar 1982 Stochastic flow reactor modeling A general continuous time compartmental model with first-order reactions In Residence Time Distribution Theory in Chemica Engineering A. Petho and R D Noble pp 75 101, Verlag Chemie GmbH Weinheim

Feller, W 1950 Probability Theory and Its Applications John Wiley, New York

Ferguson, G A , S D Klausner and W S Reid 1988 Synchronizing Nitrogen Additions with Crop Demand to Protect Groundwater In New York s Food and Life Sciences Groundwater Protection New York Agricultural Experiment Station Cornell University Agricultural Experiment Station Cornell University, Ithaca, New York 14853 Vol 18 Nos 1 & 2

Fetter, C W 1993 Contaminant Hydrology Macmillan Publishing Company New York, New York.

Food and Agricultural Organization (FAO) 1990 Fertilizer yearbook Vol 40 Food and Agric Org of the United Nations, Rome, Italy

Frissel, M J , and J A van Veen (eds) 1981 Simulation of nitrogen behavior of soil-plant systems Centre for Agricultural Publishing and Documentation, PUDOC, Wageningen, The Netherlands

Gaber, H M , W P Inskeep S D Comfort and J M Wraith 1995 Nonequilibrium Transport of Atrazine through Large Intact Soil cores Soil Sci Soc Am J 59 60-67

Gallagher, R N , C O Weldon and J G Futral 1975 An aluminum block digester for plant and soil analysis Soil Sci Soc Amer Proc 39 803-806

Gamerdinger, A P , A T Lemley and R J Wagenet 1991 Nonequilibrium Sorption and Degradation of Three 2-Chloro-s-Triazine Herbicides in Soil-Water Systems J Environ Qual 20 815-822

Gilmour, P. 1973. General validation procedure for computer simulation models. Australian Computer Journal 5:127-130.

Godwin, D.C., and C.A. Jones. 1991. Nitrogen dynamics in soil-plant systems. p. 287-321. In J. Hanks and J.T. Ritchie (eds.) Modeling plant and soil systems. Agronomy Monograph no. 31. ASA CSSA SSSA, Madison, WI.

Gordon, A.S., and F.J. Millero. 1985. Adsorption mediated decrease in the biodegradation rate of organic compounds. Microb. Ecol. 11:289-298.

Goulding, C.J. 1979. Validation of growth models used in forest management. New Zealand J. For. 24:180-214.

Graetz, D.A., L.C. Hammond, and J.M. Davidson. 1973. Nitrate movement in Eusis fine sand planted to millet. Soil Crop Sci. Soc. Fl. Proc., 33:157-160.

Green, R.E., and S.W. Karickhoff. 1990. Sorption estimates for modeling. In Pesticides in the Soil Environment: Processes, Impacts, and Modeling, ed. H.H. Cheng, pp. 79-101. Soil Science Society of America. Madison, WI.

Hageman, R.H. 1984. Ammonium versusnitrate nutrition of higher plants. p. 67-85. In R.D. Hauck (ed.). Nitrogen in crop production. Proc. Symposium Nat. Fert. Dev. Center Tenn. Valley Auth., ASA, CSSA and SSSA, Sheffield, AL. 25-27 May 1982. ASA CSSA. SSSA, Madison, WI.

Hallberg, G.R. 1989. Pesticide pollution of groundwater in the humid United States. Agriculture, Ecosystems, and Environment 26:299-367.

Hambleton, L.G. 1977. Semiautomated method for simultaneous determination of phosphorus, calcium, and crude protein in animal feeds. J. Assoc. Off. Anal. Chem. 60:845-852.

Hammond, L.C., and J.M. Bennett. 1988. Scheduling Irrigation for Corn in the Southeast. ARS-65, USDA. pp. 123-153.

Hammond, L.C., R.B. Campbell, and E.D. Threadgill. 1981. Irrigation management strategies for humid regions. In Irrigation Scheduling for Water and Energy Conservation in the 80's. Proc. Irrigation Scheduling Conf., ASAE, Chicago. Dec. 14-15. pp. 36-44.

Hanks, R.J., and S.A. Bowers. 1962. Numerical solution of the moisture flow equations for infiltration into layered soils. Soil Sci. Am. Proc. 26:530-534.

Hughes, J L 1975 Evaluation of groundwater degradation resulting from waste disposal to alluvium near Barstow California U S Geological Survey Professional Paper 878

Hutson, J L , and R J Wagenet 1988 Simulating the fate of diazinon, simazine and bromide in a field soil Factors influencing the assessment of model performance In International Conference and Workshop on Validation of Flow and Transport Models for the Unsaturated Zone, P J Wierenga and D Bachelet, (eds) pp 158-166 New Mexico State University, Las Cruces, NM

Hutson, J L., R J Wagnet, and J J Troiano 1988 Simulating the fate of diazanon, simazine and bromide in a field soil Factors influencing the assessment of model performance In P.J Wierenga and D Bachelet (Eds), Proceedings of the International Conference and Workshop on Validation of Flow and Transport Models for the Unsaturated Zone, Ruidoso NM May 23-26

Hutson J L , and R J Wagnet 1989 LEACHM Leaching Estimation And Chemistry Model A process based model of water and solute movement, transformations plant uptake and chemical reactions in the unsaturated zone, Version 2 Continuum Vol 2 New York State Water Resource Inst Cornell University Ithaca New York, 14853

Hutson, J L., and R.J Wagnet, 1991 Simulating nitrogen dynamics in soils using a deterministic model Soil Use and Management 7 74-78

Hutson, J L , and R J Wagnet 1992 LEACHM Leaching Estimation And Chemistry Model A process-based model of water and solute movement, transformations plant uptake and chemical reactions in the unsaturated zone New York State College of Agriculture and Life Sciences, Cornell University, Ithaca, New York, 14853

Huwe B and R R van der Ploeg 1988 Development and validation of a soil nitrogen simulation model International Conference and Workshop on the Validation of Flow and Transport Models for the Unsaturated Zone Inn of the Mountain Gods, Ruidoso, NM, May 22-15, 1988

Hyzak, D L , and R L Zimdahl 1974 Rate of degradation of metribuzine and two analogs in soils Weed Science 22 75-79

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) 1982 Annual Report for 1981 Patancheru, India

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) 1983 Annual Report for 1982 Patancheru, India

International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT). 1990. Documentation for IBSNAT crop model input and output files, Version 1.1. for the Decision Support System for Agrotechnology Transfer (DSSAT V 2.1). IBSNAT Technical Report 5. University of Hawaii, Honolulu, HI.

Ivie, J.O., and L.A. Richards. 1937. A meter for recording slow liquid flow. Rev. Sci. Instr. 8:86-89.

Jones, L.R. 1986. Field, Laboratory, and Modeling Studies on the Degradation and Transport of Aldicarb Residues in Soil and Ground Water. American Chemical Society 0097-6156/86/0315-0197.

Jones, A.J., and R.J. Wagenet. 1984. In Situ Estimation of Hydraulic Conductivity Using Simplified Methods. Water Resour. Res. 20:1620-1626.

Jones, W.J., J.W. Mishoe, and J.K. Boote. 1987. Introduction to simulation and modeling. Tech. Bull. no. 10. Food and Fertilizer Tech. Center, Taipei, Taiwan, Republic of China.

Jones, W.J., K.J. Boote, G. Hoogenboom, S.S. Jagtap, and G.G. Wilkerson. 1989. SOYGRO V5.42, Soybean crop growth simulation model. User's guide. Florida Agric. Exp. Stn., Journal no. 8304. University of Florida, Gainesville.

Jones, J.W., B. Zur and J.M. Bennett. 1986. Interactive effects of water and nitrogen stresses on carbon and water vapor exchange of corn canopies. Agric. For. Meteorol. ,38:113-126.

Johnston, H. 1972. Newly recognized vital nitrogen cycle. Proc. Nat. Acad. Sci. 69:2369-2372.

Jordan, L.S., W.J. Farmer, J.R. Goodin, and B.E. Day. 1970. Nonbiological detoxification of the s-triazine herbicides. Residue Review 32:267-270.

Jourdan, S. 1993. Soil Analysis by Immunoassay. Focus on Atrazine. Ohmicronicles Vol. 1 No. 2. 1993.

Jury, W.A., G. Sposito, and R.E. White. 1986. A transfer function model of solute transport through soil. 1. Fundamental concepts. Water Resour. Res. 22:243-247.

Kanwar, J.S. 1978. Fertilization of sorghum, millets and other food crops for optimum yields under dry farming conditions. Pages AGRI II 3/1-16 in Proceedings of the Annual Seminar, Dec. 1099. New Delhi 110067 India. Fertilizer Association of India (FAI).

Keeney, D R 1982 Nitrogen management for maximum efficiency and minimum pollution In F J Stevenson (ed) Nitrogen in Agricultural Soils Monograph No 22 Amer Soc Agron , Madison, WI, pp 605-649

Knighton, R E , and R J Wagenet. 1987 Simulation of Solute Transport Using a Continuous Time Markov Process 1 Theory and Steady State Application Water Resource Research 23 1911-1916

Knisel, W G (ed) 1980 CREAMS A Field Scale Model for Chemicals, Runoff and Eroston from Agricultural Management Systems U S Department of Agriculture Conservation Research Report No 26 Washington, DC 640 pp

Koo, R C J C A Anderson 1 Stewart D P H Tucker, D V Calvert, and H K Wutscher 1984 Recommended fertilizers and nutritional sprays for citrus Univ of Fla IFAS Bull No 536D pp 30

Kumar, V , and K S Awasthi 1977 Efficiency of different manures in relation to their effect on yield and nutrient uptake by grain sorghum Agrochimica 21 327-334

Lanjewar B R , and B D Khot 1977 Effect of nitrogen, phosphate and spacing on nutrient uptake by two sorghum varieties Journal of Maharashtra Agricultural Universities 2 123-126

Leij, J F , J H Dane and M Th van Genuchten 1991 Mathematical Analysis of One-Dimentional Solute Transport in a Layered Soil Profile Soil Sci Soc Am J 55 944-953

Leonard R A , W G Knisel, and D A Still 1987 GLEAMS Groundwater Loading Effects of Agricultural Management Systems Transactions of the ASAE 30 1403-1418

Lemcoff, J H and R S Loomis 1986 Crop ecology, production and management Crop Sci 26 1017-1022

Levitt, J 1980 Responses of Plants to Environmental Stresses Vol II Water Radiation, Salt and Other Stresses Academic Press Inc Second Edition 607 p

League, K M , R E Green, and L A Mulkey 1988 Evaluation of mathematical models of solute migration and transformation An overview and an example In Proceedings of International Conference and Workshop on Validation of Flow and Transport Models for the Unsaturated Zone, P J Wierenga and D Bachelet, pp 231-248, New Mexico State University, Las Cruces NM

Lord, E I and G Bland 1991 Leaching of spring-applied fertilizer nitrogen measurement and simulation Soil Use and Management, 7 110-114

Madsen, E L 1985 Effects of chemical speciation on microbial mineralization of organic compounds Ph D Dissertation Cornell University, Ithaca, NY (Diss Abstr 85-04534)

Martin, D L, D G Watts, L N Mielke, K D Frank and D E Eisenhauer 1982 Evaluation of nitrogen and irrigation management for corn production using water high in nitrate. Soil Sci Amer Proc 46 1056-1061

Mbuya, O S 1990 Influence of Shade, Intercropping and Spatial Arrangement of Maize and Bean on Growth and Yield Components of Beans M S Thesis, Department of Agronomy, University of Florida 124 pp

McCasland, M , N M Trautmann, K S Porter, and R J Wagenet 1985 Nitrate Health Effects in Drinking Water Natural Resources Cornell Cooperative Extension Fact Sheet Page 400 02

McElroy, M B , and J C McConnell 1971 Nitrous oxide A natural source of stratospheric NO Journal of Atmospheric Science 28 1095 1098

Mehran, M., and K K Tanji 1974 Computer modeling of nitrogen transformations in soils J Environ Qual 3 391 396

Miller, M E, and M Alexander 1991 Kinetics of bacterial degradation of benzylamine in a montmorillonite suspension Environ Sci Technol 25 240-245

Moraghan, J T., T J Buresh, R J Vlek, P L Burford Jr., S Singh and K L Sahrawat 1983 Labelled nitrogen fertilizer studies on a vertisol in the semi-arid tropics In ICRISAT Annual Report, 1983

Muir, D C G , and B E Baker 1978 The disappearance and movement of three triazine herbicides and several of their degradation products in soil under field conditions Weed Research 18 111-120

Myers, R J K and C J Asher 1981 Mineral Nutrition of Grain Sorghum Macronutrients In Sorghum in the Eighties Proc of the International Symposium on Sorghum Vol 1 pp 161-177 2-7 Nov 1981 ICRISAT Center Patancheru, A P India.

Nagre, K T , and B G Bathkal 1978 Studies on the NPK requirents of sorghum hybrid CSH-1 under *kharif* rainfed conditions Journal of Mahrashtra Agricultural Universities 4 113-115

Nash, R G 1988 Dissipation from soil In Environmental Chemistry of Herbicides Vol I eds R Grover pp 131-170 Boca Raton, FL CRS Press

Nassar, R , L T Fan, J R Too, and L A Disrud 1982 Application of a stochastic soil erosion model Pap 82-2574, Am Soc of Agric Eng Chicago Il

National Academy of Sciences (NAS) 1984 Groundwater Contamination National Academy Press, Washington, DC 179 p

Nnelamkavil, F 1986 Computer Simulation and Modeling John Wiley and Sons, New York.

Nielsen D R and J W Biggar 1962 Miscible displacement III Theoretical considerations Soil Sci Soc Am Proc 26 216-221

Nielsen, D R , P J Wierenga, and J W Biggar 1982 Nitrogen transport processes in soil In F J Stevenson (ed) Nitrogen in Agricultural Soils Monograph No 22 Amer Soc Agron Madison, WI, pp 423-442

Nielsen D R , J W Biggar, and K T Erh 1973 Spatial variability of field measured soil-water properties Hilgardia 42 215-259

Nimah, M N , and R J Hanks 1973 Model estimation of soil water plant and atmospheric interrelations I Description and sensitivity Soil Sci Amer Proc 37 522-527

Nkedi-Kizza, P , P S C Rao and J W Johnson 1983 Adsoption of Diuron and 2,4,5-T on Soil Particle-Size Separates Journal of Environ Qual 12 195-197

Office of Technology Assessment (OTA) 1984 Protecting the Nation s Groundwater from Contamination Washington, D C U S Congress OTA 0-276, two volumes

Ohmicron RaPID Assay Kit Manual 1993 Ohmicron Corporation, Newtown, PA

Olson, R A , R F Hensler, O J Attoe, S A Witzwl, and G A Peterson 1970 Fertilizer N and crop rotation in relation to movement of nitrate N through soil profiles Soil Sci Soc Am Proc 34 448-452

Olson, R V and L T Kurtz 1982 Crop nitrogen requirements utilization and fertilization p 567-604 In F J Stevenson (ed) Nitrogen in agricultural soils Agronomy Monograph no 22 ASA CSSA SSSA Madison, WI

Omoko M 1989 Influence of Crop-Water Management on Yield Water Use Relationships Ph D Dissertation, Department of Soil Science, University of Florida. 282 pp

Pearce, R.B., and D.O. Lee. 1969. Photosynthetic and morphological adaptation of alfalfa leaves to light intensity at different stages of maturity. Crop Sci. 9:791-794.

Pennell, K.D., A.G. Hornsby, R.E. Jessup, and P.S.C. Rao. 1990. Evaluation of Five Simulation Models for Predicting Aldicarb and Bromide Behavior Under Field Conditions. Water Resour. Res. 26:2679-2693.

Petach, M.C., R.J. Wagenet, and S.D. DeGloria. 1991. Regional water flow and pesticide leaching using simulations with spatially distributed data. Ganderma 48:245-269.

Power, J.F., and Schepers. 1989. Nitrate contamination of groundwater in North America. Agric. Ecosystem and Environ. 26:165-187.

Pye, V., R. Patrick, and J. Quarels. 1983. Groundwater contamination in the United States. University of Pennsylvania Press. 315 p.

Rao, P.S.C. 1988. Criteria for Monitoring Organic Pollutants in Groundwater. Soil Science Fact Sheet SL-56. Florida Cooperative Extension Services/Institute of Food and Agricultural Sciences/University of Florida.

Rao, P.S.C., and W.M. Alley. 1993. Pesticides. In Regional Groundwater Quality. W.M. Alley (ed.). Van Nostrand Reinhold, New York.

Rao, P.S.C., C.A. Bellin, and M.L. Brusseau. 1993. Coupling Biodegradation of Organic Chemicals to Sorption and Transport in Soils and Aquifers: Paradigms and Paradoxes. In Sorption and Degradation of Pesticides and Organic Chemicals in Soil. SSSA Special Publication no.32.

Rao, P.S.C., V.E. Berkheiser and L.T. Ou. 1984. Estimation of Parameters for Modeling the Behavior of Selected Pesticides and Orthophosphate. Washington DC. USEPA-600/3-84-019.

Rao, P.S.C., J.M. Davidson, R.E. Jessup, and K.R. Reddy. 1984. Nitrogen behavior in croplands receiving organic wastes: Development and verification of a simulation model (NITROSIM). Institute of Food and Agricultural Sciences Monograph. University of Florida.

Rao, P.S.C., J.M. Davidson, and R.E. Jessup. 1981. Simulation of nitrogen behavior in the root zone of cropped land areas receiving organic wastes. p. 81-95. In Simulation of nitrogen of Soil-Plant Systems. M.J. Frissel and J.A. van Veen (eds.). Centre for Agricultural Publishing and Documentation, PUDOC. Wageningen, The Netherlands.

Rao, P.S.C., and J.M. Davidson. 1980. Estimation of pesticide retention and transformation parameters required in nonpoint source pollution models. In: Environmental Impacts of Nonpoint Source Pollution. eds. M.R. Overcrash and J.M. Davidson, pp. 23-67. Ann Arbor, MI: Ann Arbor Science Publishers.

Rao, P.S.C., and A.G. Hornsby. 1989. Behavior of Pesticides in Soils and Water. Gainesville, FL: Institute of Food and Agricultural Sciences, University of Florida. Soil Science Fact Sheet SL-40.

Rao, P.S.C., A.G. Hornsby, and R.E. Jessup. 1985. Indices for ranking the potential for pesticide contamination of groundwater. Proceedings Soil and Crop Science Society of Florida. 44:1-8.

Rao, P.S.C., and R.E. Jessup. 1982. Development and verification of simulation models for describing pesticide dynamics in soils. Ecological Modeling. 16:67-75.

Rao, P.S.C., R.S. Mansell, L.B. Baldwin, and M.F. Laurent. 1983. Pesticides and their behavior in soils and water. Soil Sci. Fact Sheet SL-40. Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL.

Rao, P.S.C., R.E. Jessup, and K.R. Reddy. 1984. Simulation of Nitrogen Dynamics in Flooded Soils. Soil Science. 138:54-62.

Rao, P.S.C., H.M. Selim, J.M. Davidson, and D.A. Graetz. 1975. Simulation of Transformations, Ion-Exchange and transport of Selected Nitrogen Species in Soils. Soil and Crop Science Society of Florida. 35:161-164.

Reddy, K.S., H.A. Mills, and J.B. Jones. 1991. Corn responses to post tasseling nitrogen deprivation and to various ammonium/nitrate ratios. Agron. J. 83:201-203.

Reddy, C.K., A. Venkatachary, and K.A. Reddy. 1978. Performance of sorghum varieties with three levels of nitrogen under rainfed and irrigated conditions. Madras Agricultural Journal. 65:406-408.

Richards, L.A. 1931. Capillary conduction of liquids in porous mediums. Physics. 1:318-333.

Richards, L.A., M.B. Russel, and O.R. Neal. 1937. Further developments on apparatus for field moisture studies. Soil Sci. Soc. Am. Proc. 1:55-63.

Richard, J.J., G.A. Junk, M.J. Avery, N.L. Nehring, J.S. Fritz, and H.J. Svec. 1975. Analysis of various Iowa waters for selected pesticides: Atrazine, DDE, and dieldrin-1974. Pesticide Monitoring Review. 9:117-123.

Ritchie, J., U. Singh, D. Godwin, and L. Hunt. 1989. A user's guide to CERES Maize-V2.10. IFDC. Muscle Shoals, AL.

Ritter, W.F. 1990. Pesticide contamination of ground water in the United States - A review. Journal of Environmental Science and Health B25:1-29.

Robinson, K.G., W.S. Farmer, and J.T. Novak. 1990. Availability of sorbed toluene in soils for biodegradation by acclimated bacteria. Water Res. 24:345-350.

Rose, C.W., and W.R. Stern. 1965. The drainage component of the water balance equation. Aust. J. Soil Res. 3:95-100.

Ross, P.J. 1990. Efficient numerical methods for infiltration using Richards' Equation. Water resour. Res. 26:279-290.

Roy, R.N., and B.C. Wright. 1974. Sorghum growth and nutrient uptake in relation to soil fertility: II. N, P, and K uptake pattern by various plant parts. Agronomy Journal 66:5-10.

Russo, D., and E. Bresler. 1981. Soil hydraulic properties as stochastic processes: I. An analysis of field spatial variability. Soil Sci. Soc. Am. J. 45:682-687.

Saarinen, P.P., and Lynne, G.D. 1993. Allocating Water Under Scarcity Conditions in Florida: Evaluation and Prospectus. Economics Report ER 93-2.

SAS Institute Inc. 1988. SAS/STAT User's Guide, Release 6.03 edition. Statistics Analysis Systems Institute Inc., Cary, NC.

Saxton, K.E., G.E. Schuman, and R.E. Burwell. 1977. Modeling nitrate movement and dissipation in fertilized soils. Soil Sci. Soc. Am. J. 41:265-271.

Schrader, L.E. 1984. Functions and transformations of nitrogenin higher plants. p. 55-65. In R.D. Hauck (ed.) Nitrogen in crop production. Proc. Symposium Nat. Fert. Dev. Center Tenn. Valley Auth., ASA, CSSA and SSSA, Sheffield, AL. 25-27 May 1982. ASA CSSA, SSSA. Madison, WI.

Schepers, J.S., M.G. Moravek, E.E. Alberts, and K.D. Frank. 1991. Maize production impacts on ground water quality. J. Environ. Qual. 23:105-110.

Scow, K.M. 1990. Rate of biodegradation. In Handbook of Chemical Property Estimation Methods, eds. W.J. Lyman, W.F. Reehl and D.H. Rosenblatt, pp.9-1 - 9-85. American Chemical Society. Washington D.C.

Scow, K M. and M. Alexander. 1992. Effect of diffusion on the kinetics of biodegradation: Experimental results with synthetic aggregates. Soil Science Society of America Journal 56:128-34.

Scow, K M., and J. Hutson. 1992. Effect of diffusion and sorption on the kinetics of biodegradation: Theoretical considerations. Soil Science Society of America Journal 56:119-27.

Shaffer, M J. 1988. Estimating confidence bands for soil-crop simulation models. Soil Sci. Soc. Am. J. 52:1782-1789.

Shankland, D L. 1985. Environmental toxicants and public risk in Florida. Soil and Crop Science Society of Florida Proceedings. Volume 33 pages 14-17.

Short, T E., and C G. Enfield. 1988. Large laboratory column study of the transport and degradation of atrazine, carbofuran, and diuron in soils. In: Jamet P. (ed.) Methodological Aspects of the Study of Pesticide Behavior in Soils. Institut national de recherche agronomique, Paris. pp. 139-150.

Silvertooth, J C., J E. Watson, J E. Malcuit, and T A. Doerge. 1992. Bromide and Nitrate Movement in an Irrigated Cotton Production System. Soil Sci. Soc. Am. J. 56:548-555.

Simmons, C.S., D R. Nielsen, and J W. Biggar. 1979. Scaling of field-measured soil water properties. I. Methodology. II. Hydraulic Conductivity and Flux. Hilgardia 47:77-174.

Simmons, S R., and R J. Jones. 1985. Contributions of pre-silking assimilate to grain yield in maize. Crop Sci. 25:29-1004-1006.

Singh, A. and S S. Bains. 1971. Consumptive use and moisture extraction pattern by sorghum (CSH-1 and Swarna) as influenced by nitrogen and plant population. Indian Journal of Agronomy 16:491-493.

Singh, M. and D P H. Tucker. 1988. Herbicide effect on tree growth and weed populations in citrus. Proc. Fla. State Hort. Soc. 101:59-61.

Singh, M., D P H. Tucker and S H. Futch. 1990. Multiple applications of pre-emergence herbicides tank mixtures in young citrus groves. Proc. Fla State Hort. Soc. 103:16-21.

Singh, P. and S D. Chubey. 1972. Effect of varying levels of nitrogen on yield and yield attributes of some sorghum varieties. Indian Journal of Agricultural Sciences 42:337-340.

Singh, U. 1991. Introduction to modeling in training program on computer simulation for crop growth and nutrient management. IFDC Muscle Shoals, AL. 6-17 May 1991. International Fertilizer Development Center. Muscle Shoals, AL.

Smith, C.N., R.A. Leonard, G.W. Langdale, and G.W. Bailey. 1978. Transport of agricultural chemicals from small upland Piedmont watersheds. USEPA. EPA-600/3-78-056. 363 pp.

Smith, M.C. 1988. Measurement and prediction of herbicide transport into shallow groundwater. Ph. D. Dissertation, Department of Agricultural Engineering, University of Florida. 214pp.

Smith, M.C., A.B. Bottcher, K.L. Campbell, and D.L. Thomas. 1991. Field Testing and Comparisons of the PRZM and GLEAMS Models. American Society of Agricultural Engineers. 34:1-838-847.

Smith, M.C., D.L. Thomas, and K.L. Campbell. 1990. Measurements of Pesticide Transport to Shallow Ground Water. American Society of Agricultural Engineers. 33:1573-1582.

Smith, S.J. and D.K. Cassel. 1991. Estimating nitrate leaching in soil materials. In: Follett, R.F., D.R. Keeney and R.M. Cruse (eds.). Managing N for ground water quality and farm profitability. Soil Sci. Soc. of America. Madison, WI. USA. pp. 165-188.

Steenhuis, T.S., S. Pacenka, and K.S. Porter. 1987. MOUSE: A management model for evaluating groundwater contamination from diffuse surface sources aided by computer graphics. Applied Agri. Research. 2:277-289.

Stevenson, F.J. (ed.). 1982. Nitrogen in Agricultural Soils. Agronomy 22. American Society of Agronomy, Madison, WI.

Stevenson, J.A. 1986. Impact of Nitrogen on Health and the Environment. pp. 216-218. In: Cycles of Soil: Carbon, Phosphorus, Sulfur, Micronutrients. J. Wiley & Sons. New York, NY.

Stotzky, G., and L.T. Rem. 1966. Influence of clay minerals of microorganisms. I. Montmorillonite and kaolinite on bacteria. Can. J. Microbiol. 12:547-563.

Subba Rao, R.V., and M. Alexander. 1982. Effect of sorption on mineralization of low concentrations of aromatic compoundsin lake water sediments. Appl. Environ. Microbiol. 44:659-668.

Tanji, K.K. 1980. Problems in modeling nonpoint sources of nitrogen in agricultural systems. In: Environmental Impact of Nonpoint Source Pollution. M.R. Overcash and J.M. Davidson (eds.). Ann Arbor Sci. Pub., pp. 165-183.

Tanji, K K 1981 Modeling the soil nitrogen cycle In Nitrogen in Agricutural Soils In F S Stevenson (ed.) Am Soc Agron Monogr 22, ASA Madison WI

Tanji, K K., and S K Gupta. 1978 Computer simulation modeling for nitrogen in irrigated croplands In Nitrogen in the environment, Vol 1, Nitrogen Behavior in Field Soil D R Nielsen and J G MacDonald, (eds) Academic Press, New York, pp 79 130

Teng, P S., and R E Gaunt 1980 Modeling systems of disease and yield loss in cereals Agricultural Systems 6 131-154

Thomas B P E Cummings and W H Wittstruck 1985 Soil survey of Alachua County Florida USDA-Soil Conservation Service U S Gov Print Office, Washington, DC

Thornley, J H M., and I R Johnson. 1990 Plant and Crop Modelling A Mathematical Approach to Plant and Crop Physiology Oxford University Press (UK)

Tillotson W R, and R J Wagenet 1982 Simulation of Fertilizer Nitrogen Under Cropped Situations Soil Science, 133 133-143

Tillotson, W R., C W Robbins, R J Wagenet and R J Hanks. 1980 Soil Water Solute and Plant Growth Simulation Utah Agricultural Experiment Station Bulletin 502

Trautmann, N M K S Porter and R J Wagenet 1985 Water and the soil Natural resources, Cornell Cooperative Extension Groundwater Soil Fact sheet Page 400 05

Troiano, J , C Garretson, C Krauter and J Brownell 1990 Atrazine leaching and its relation to percolation of water as influenced by three rates and four methods of irrigation water application Environmental Hazards Assessment Program, California Department of Food and Agriculture Division of Pest Management, Environmental Protection and Worker Safety, Environmental Monitoring and Pest Management Branch CA, EH 90-7

Tsuji, G Y, G Uehara and S Balas (eds). 1994a. DSSAT v3. Volume 1. University of Hawaii, Honolulu, Hawaii

Tsuji, G Y G Uehara and S Balas (eds) 1994b DSSAT v3 Volume 2 University of Hawaii, Honolulu, Hawaii

U S Environmental Protection Agency (USEPA). 1976 Quality criteria for water U S Govt Print. Office, Washington, DC

U S Environmental Protection Agency (USEPA) 1988 Pesticides in groundwater data base 1988 interim report. Washington, DC Office of Pesticide Programs

U S Environmental Protection Agency USEPA) 1990a. Findings and results p 51-88 In National survey of pesticides in drinking water wells Phase I report USEPA Rep 570/9-90-015. U.S. Gov. Print Office Washington, DC.

U S Environmental Protection Agency (USEPA) 1990b National pesticide survey Summary results of EPA s national survey of pesticides in drinking water wells Office of Water and Office of Pesticides and Toxic Substances, USEPA, Washington, DC

U S Department of Agriculture (USDA). 1991. Nitrate occurance in U.S. waters (and related questions). (Prepared by J. Fedwick). U S Government Printing Office 1991-281-372/52001

van Loosdrecht, M C M , J Lyklema, W Norde, and A J B Zehnder 1990 Influences of interfaces on microbial activity Microbiol Rev 54 75-87

Venkateswarlu, J. and U M B Rao 1978. Relative response of different crops to fertilizer phosphorus In semi-arid red soils Pages 404-407 In Phosphorus in soils crops and fertilizers Bulletin 12 New Delhi 110012 India Indian Society of Soil Science

Vlek P L.G , I R P Fillery, and J R Burford 1981 Accession, transformation and loss of nitrogen in soils of the arid regions Plant and Science 58 133-175

Wagenet, R J 1983 Principles of Salt Movement in Soils In Chemical Mobility and Reactivity in Soil Systems pp 123-141 ASA SSSA, 677 South Segoe Rd , Madison WI

Wagenet, R J. 1986a Principles of Modeling Pesticide Movement in the Unsaturated Zone In Evaluation of Pesticides in Ground Water, W. Y Garner, R. C Honeycutt, and H N Nigg (eds) American Chemical Society Symposium Series 315 p 331-341

Wagenet, R J 1986b Water and Solute Flux In Methods of Soil Analysis, Part 1 Physical and Mineralogical Methods - Agronomy Monograph no 9 ASA SSSA Madison, WI. USA.

Wagenet, R.J 1987. Processes influencing pesticide loss with water under conservation tillage In Terry et al (eds) Effects of Conservation Tillage on Groundwater Quality Nitrates and Pesticides Lewis Publishers, Inc , Chelsea, Michigan

Wagenet, R.J 1991a Why model Aspects of Applied Biology 26 1-4.

Wagenet, R.J 1991b The future of modeling Aspects of Applied Biology 26 209-216

Wagenet, R J. and J L Hutson 1986 Predicting the fate of nonvolatile pesticides in the unsaturated zone. J. Environ. Qual , 15 315-322

Wagenet, R J and J L Hutson. 1989 LEACHM A process-based model of water and solute movement transformations, plant uptake and chemical reactions in the unsaturated zone Version 2 0 Continuum, Vol 2 New York State Resources Inst , Cornell Univ Ithaca New York 1989

Wagenet R J and J L Hutson 1990 Quantifying pesticide behavior in soil Annu Rev Phytopathol , 28 295 319

Wagenet, R J and B Rao 1983 Description of nitrogen movement in the presence of spatially variable soil hydraulic properties Agricultural Water Magement, 6 227 242

Wagenet, R J and P S C Rao 1985 Basic Concepts of Modeling Pesticide Fate in the Crop Root Zone Weed Science 33 25-32

Wagenet, R J , and P S C Rao 1990 Modeling Pesticide Fate in Soils In Pesticides in the Soil Environment - Soil Science Society of America Book series no 2 Chapter 10 p 351-399

Warrick, A W G J Mullen and D R Nielsen 1977a Scaling of field measured soil hydraulic properties using a similar media concept Water Resour Res 13 355 362

Warrick, A W , G J Mullen, and D R Nielsen. 1977b Predictions of soil water flux based upon field measured soil water properties Soil Sci Soc Am J 41 14-19

Watts, D G and R J Hanks 1978 A soil water nitrogen model for irrigated corn on sandy soils Soil Sci Soc Amer Proc 42 492-499

Watts, D G and D L Martin 1981 Effects of water and nitrogen management on nitrate leaching loss from sands Transactions of the Amer Soc Agric Engin pp 911-916

Wauchope R D 1978 The pesticide content of surface water draining from agricultural fields - A review J Environ. Qual 7 459-472

Wauchope, R D ,T M Butler, A G Hornsby, P W M Augustijn Becker, and J P Burt 1991 The SCS/ARS/CES pesticides properties database for environmental decision making Reviews in Environmental Contaminant Toxicology 123 1-155

Weber, E J 1991 Studies of benzidine-based dyes in sediment-water systems Environ Toxicol Chem 10 609 618

Weber, J B , and H D Cobie 1968 Microbial decomposition of diquat adsorbed on montmorillonite and kaolinite clays J Agric Food Chem 16 475-478

Weil, R.R., R.A. Weismiller, and R.S. Turner. 1990. Nitrate contamination of groundwater under irrigated Coastal Plain soils. J. Environ. Qual. 19:441-448.

Whisler, F.D., B. Acock, D.N. Baker, R.E. Fye, H.F. Hodges, J.R. Lambert, H.E. Lemmon, J.M. McKinion, and V.R. Reddy. 1986. Crop simulation models in agronomic systems. Adv. Agron. 40:141-208.

Whitmore, A.P. 1991. A method for assessing the goodness of computer simulation of soil processes. J. Soil Sci. 42:289-299.

Wilkerson, G.G., J.W. Jones, K.J. Boote, K.T. Ingram, and J.W. Mishoe. 1983. Modeling soybean growth for crop management. Transaction of the ASAE 26:63-73.

Wilkerson, G.G., J.W. Jones, K.J. Boote, and J.W. Mishoe. 1985. SOYGRO V5.0. Soybean crop growth and yield model. Gainesville, Florida, USA: University of Florida.

Williams, J.R. and W.V. LaSeur. 1976. Water yield modeling using SCS curve numbers. J. Hydraulics Div., ASCE 98(HY12):2087-2098.

Williams, W.M., P.W. Holden, D.W. Parsons, and M.N. Lorber, 1988. Pesticides in Ground water Data Base 1988 Interim Report. U.S.E.P.A. Office of Pesticides Programs, Environmental Fate & Effects Division, Environmental Fate & Groundwater Branch. December, 1988.

Wischmeier, W.H. and D.D. Smith. 1978. Predicting rainfall erosion losses. U.S. Dept. of Agriculture, Agriculture Handbook No. 537. Washington, DC.

Wollenhaupt, N.C. and R.E. Stringman. 1990. Atrazine in groundwater: A current perspective. University of Wisconsin-Extension, Agricultural Bulletin G3525, 17 pp.

Wosten, J.H.M., J. Bouma, and G.H. Stoffelsen. 1985. Use of soil survey data for regional soil water simulation models. Soil Sci. Soc. Am. J., 49:1238-1244.

Wszolek, P.C., and M. Alexander. 1979. Effect of desorption rate on the biodegradation of *n*-alkyamines bound clay. J. Agric. Food Chem. 27:410-414.

Zimdahl, R.H., and S.M. Gwynn. 1977. Soil degradation of three dinitroanilines. Weed Science 25:247-251.

APPENDIX A

WEATHER, CROP AND SOIL DATA

Table A 1 Weather data at the experimental site between April 1 and August 4, 1991

Month	Day	Maximum Temp	Minimum Temp	Soil† Temp	Rainfall	Solar Radiation
		°C			mm	MJ m⁻²
APR	1	24.5	9.0	16.2	0	26.39
APR	2	26.5	5.4	16.2	0	26.03
APR	3	25.9	9.4	18.3	0	19.64
APR	4	27.6	15.0	20.3	0	18.93
APR	5	28.1	18.3	21.9	0	17.15
APR	6	28.9	16.0	22.2	0	20.31
APR	7	30.0	18.9	23.1	0	21.19
APR	8	30.0	19.4	23.4	2	17.89
APR	9	30.5	18.4	23.4	17	22.88
APR	10	29.5	17.5	22.1	33	17.97
APR	11	31.4	15.9	22.9	0	23.16
APR	12	29.3	18.9	23.2	0	21.74
APR	13	29.5	18.3	23.5	0	21.44
APR	14	30.1	17.5	23.6	0	25.78
APR	15	31.2	18.6	23.3	0	19.41
APR	16	32.2	16.6	24.3	0	24.81
APR	17	26.0	18.0	21.1	32	11.25
APR	18	28.8	18.0	22.0	0	20.42
APR	19	28.9	17.3	22.0	0	13.80
APR	20	28.4	15.2	19.8	27	17.52
APR	21	23.8	12.2	17.5	1	27.73
APR	22	27.0	10.0	17.8	0	25.17
APR	23	24.6	15.8	20.3	7	6.09
APR	24	31.2	19.3	24.5	0	24.50
APR	25	22.7	18.1	20.0	33	2.36
APR	26	28.8	16.8	22.1	1	13.29
APR	27	33.0	20.0	25.2	0	23.47
APR	28	33.2	19.9	25.9	0	22.25
APR	29	33.2	20.5	26.6	0	28.25
APR	30	33.2	21.6	26.6	0	24.16

† Soil temperature measured at 1 m depth.

Table A.1 continued

Month	Day	Maximum Temp	Minimum Temp	Soil Temp	Rainfall	Solar Radiation
		°C	°C	°C	mm	MJ
MAY	1	32.8	19.8	25.1	0	22.24
MAY	2	32.5	17.4	26.5	0	27.53
MAY	3	32.0	16.1	23.8	0	25.56
MAY	4	32.5	18.4	25.1	0	26.22
MAY	5	32.6	18.6	25.6	0	25.52
MAY	6	31.5	18.6	22.7	7	14.87
MAY	7	32.3	17.2	23.5	2	20.33
MAY	8	31.6	21.7	25.4	0	21.80
MAY	9	31.9	20.3	25.1	0	24.76
MAY	10	32.5	20.4	25.6	0	24.98
MAY	11	31.7	19.8	23.2	13	13.50
MAY	12	31.0	17.3	24.0	0	26.63
MAY	13	31.0	18.3	24.4	0	23.87
MAY	14	32.2	20.3	25.6	0	26.00
MAY	15	33.3	20.5	26.2	0	26.34
MAY	16	34.5	18.6	25.1	16	25.63
MAY	17	32.1	19.6	25.0	0	26.37
MAY	18	32.7	21.1	26.3	0	27.50
MAY	19	31.2	21.3	24.7	21	10.27
MAY	20	30.6	22.0	25.4	1	18.20
MAY	21	29.5	21.7	25.3	0	17.20
MAY	22	29.4	23.5	25.5	0	15.03
MAY	23	27.5	21.3	23.6	8	8.65
MAY	24	30.3	21.9	24.4	20	11.62
MAY	25	32.1	22.1	26.3	0	24.41
MAY	26	33.1	22.2	24.1	11	10.03
MAY	27	32.8	22.0	25.4	8	22.91
MAY	28	32.7	21.8	26.6	0	25.55
MAY	29	34.9	21.1	26.9	14	26.22
MAY	30	32.3	21.5	25.9	0	17.62
MAY	31	33.3	18.9	22.4	19	11.69

Table A-1 continued.

Month	Day	Maximum Temp.	Minimum Temp.	Soil Temp.	Rainfall	Solar Radiation
		°C			mm	MJ m^{-2}
JUN	1	31.7	18.2	24.9	0	22.38
JUN	2	31.8	21.5	25.8	0	25.74
JUN	3	33.0	20.9	25.3	0	24.83
JUN	4	33.3	20.0	25.4	9	14.02
JUN	5	32.3	19.6	23.3	50	16.52
JUN	6	25.0	17.6	21.6	15	6.52
JUN	7	23.3	16.2	19.5	9	11.08
JUN	8	29.9	16.4	22.9	0	26.34
JUN	9	31.4	18.8	24.1	0	25.04
JUN	10	31.4	18.1	24.3	0	25.33
JUN	11	32.5	16.7	24.5	0	28.73
JUN	12	32.8	17.1	25.0	0	23.13
JUN	13	33.7	16.9	25.3	0	22.85
JUN	14	33.9	19.6	26.6	0	26.37
JUN	15	34.8	21.2	27.0	0	23.94
JUN	16	35.0	20.6	27.2	0	25.99
JUN	17	35.9	21.2	26.3	3	23.21
JUN	18	31.5	21.0	25.8	0	20.43
JUN	19	32.3	22.1	25.2	9	14.63
JUN	20	34.5	21.6	27.6	0	27.00
JUN	21	34.7	22.1	28.1	0	25.93
JUN	22	35.5	21.0	27.5	3	25.08
JUN	23	35.1	21.0	27.5	1	23.90
JUN	24	35.4	21.5	26.1	7	21.65
JUN	25	33.3	21.4	26.2	1	25.28
JUN	26	33.6	21.6	25.1	21	21.05
JUN	27	33.6	21.0	26.4	1	23.74
JUN	28	34.5	21.5	27.9	0	26.29
JUN	29	33.3	22.7	25.2	4	13.88
JUN	30	31.9	22.5	26.7	2	23.22

Table A.1 continued

Month	Day	Maximum Temp	Minimum Temp	Soil Temp	Rainfall	Solar Radiation
		°C			mm	MJ m^{-2}
JUL	1					
JUL	2	33.0	22.7	26.9	0	21.38
JUL	3	34.3	22.3	27.6	0	25.50
JUL	4	34.7	23.2	28.2	0	25.19
JUL	5	32.6	23.0	26.3	8	19.85
JUL	6	32.9	22.9	26.1	7	15.30
JUL	7	34.7	21.0	27.3	0	26.66
JUL	8	35.2	21.3	26.5	2	23.36
JUL	9	30.6	22.1	24.3	26	12.09
JUL	10	33.8	20.9	25.8	20	21.77
JUL	11	31.3	21.2	23.8	0	11.80
JUL	12	28.6	21.2	24.8	2	8.582
JUL	13	31.5	23.5	26.4	0	12.81
JUL	14	35.3	22.9	25.9	1	16.43
JUL	15	33.4	22.4	25.9	0	20.86
JUL	16	34.1	21.4	25.7	2	21.00
JUL	17	33.8	21.2	24.9	30	18.82
JUL	18	33.8	21.1	25.0	0	18.85
JUL	19	35.8	21.1	25.4	39	20.01
JUL	20	33.7	21.1	25.8	1	19.35
JUL	21	34.8	20.7	27.0	0	24.69
JUL	22	35.9	22.2	26.9	1	23.13
JUL	23	35.2	22.4	26.6	0	18.02
JUL	24	33.3	23.1	27.2	1	22.42
JUL	25	33.1	21.9	25.8	1	18.46
JUL	26	32.9	21.0	24.1	18	14.24
JUL	27	33.9	21.2	25.1	0	16.99
JUL	28	32.6	22.3	25.6	14	20.16
JUL	29	31.7	22.3	25.4	12	14.02
JUL	30	32.1	22.7	24.8	3	12.55
JUL	31	31.6	22.2	24.1	29	11.89
AUG	1	29.8	22.5	24.6	9	12.31
AUG	2	30.6	21.7	25.7	8	21.05
AUG	3	33.8	22.0	26.9	0	20.54
AUG	4	33.5	22.3	26.9	0	23.92
AUG	5	33.6	22.3	26.8	0	16.93

Table A.2 Dry weight of different plant components of sorghum at different sampling dates.

Rep	Trt†.	Fraction leaf	Fraction stem	Leaf dry wt	Stem dry wt	Total dry wt
				kg ha⁻¹		
Date: May 14, 1991						
1	1	0.74	0.26	11.9	4.2	16.2
1	2	0.72	0.28	18.1	7.1	25.2
1	3	0.70	0.30	24.6	10.2	34.7
1	4	0.71	0.29	38.4	15.7	54.1
1	5	0.69	0.31	28.7	13.0	41.8
1	6	0.70	0.30	31.4	13.2	44.6
2	1	0.70	0.30	50.7	17.8	68.4
2	2	0.72	0.28	18.1	7.0	25.1
2	3	0.69	0.31	72.3	32.3	104.6
2	4	0.71	0.29	44.0	18.1	62.1
2	5	0.67	0.33	67.4	32.6	100.0
2	6	0.67	0.33	28.6	14.0	42.6
3	1	0.71	0.29	42.0	16.8	58.8
3	2	0.73	0.27	51.8	15.5	67.3
3	3	0.72	0.28	31.8	12.1	43.9
3	4	0.73	0.27	43.1	14.8	58.9
3	5	0.74	0.26	56.2	19.8	76.0
3	6	0.73	0.27	53.4	19.6	72.9
4	1	0.72	0.28	24.7	9.8	34.5
4	2	0.75	0.25	19.8	6.7	26.5
4	3	0.76	0.24	14.2	4.1	19.2
4	4	0.75	0.25	29.5	10.1	39.6
4	5	0.96	0.05	18.1	0.9	19.0
4	6	0.76	0.24	10.4	3.7	14.2
Date: May 21, 1991						
1	1	0.65	0.35	103.4	54.6	158.0
1	2	0.66	0.34	111.2	58.9	169.1
1	3	0.68	0.32	131.9	61.9	193.8
1	4	0.64	0.36	233.9	130.1	364.0
1	5	0.66	0.34	137.5	70.1	207.6
1	6	0.68	0.32	80.0	37.3	117.3
2	1	0.67	0.33	176.1	88.7	264.8
2	2	0.69	0.31	123.7	54.7	178.4
2	3	0.63	0.37	366.6	200.6	566.2
2	4	0.64	0.36	207.3	119.0	326.3
2	5	0.62	0.38	306.1	186.0	492.1
2	6	0.69	0.31	235.6	107.7	343.3
3	1	0.65	0.35	265.0	144.6	409.6
3	2	0.66	0.34	243.8	124.2	368.0
3	3	0.67	0.33	257.7	129.0	386.7
3	4	0.66	0.34	196.6	99.0	295.6
3	5	0.66	0.34	297.0	147.6	444.4
3	6	0.63	0.37	316.2	185.3	498.6
4	1	0.67	0.33	145.1	71.2	216.3
4	2	0.67	0.33	166.6	79.6	246.1
4	3	0.70	0.30	133.9	66.7	190.6
4	4	0.63	0.37	202.6	117.1	319.7
4	5	0.70	0.30	126.9	53.7	180.6
4	6	0.69	0.31	141.3	64.7	206.0

† 1=Opt Irrig x 100 kg N ha⁻¹, 2=Mod Irrig x 100 kg N ha⁻¹, 3=Rainfed x 100 kg N ha⁻¹
4=Opt Irrig x 300 kg N ha⁻¹, 5=Mod Irrig x 300 kg N ha⁻¹, 6=Rainfed x 300 kg N ha⁻¹

Table A.2 continued

Rep.	Trt.	Fraction leaf	Fraction stem	Leaf dry wt	Stem dry wt	Total dry wt
				kg ha^{-1}		
Date: May 28, 1991						
1	1	0.53	0.37	313.5	181.7	495.2
1	2	0.60	0.40	333.9	225.0	558.9
1	3	0.63	0.38	225.0	135.6	361.6
1	4	0.65	0.35	425.9	233.9	660.8
1	5	0.61	0.39	304.5	195.0	499.6
1	6	0.62	0.38	528.4	325.0	853.4
2	1	0.60	0.50	309.7	210.7	520.5
2	2	0.55	0.36	305.3	173.2	578.5
2	3	0.60	0.40	490.9	317.6	798.5
2	4	0.60	0.40	325.4	218.3	543.7
2	5	0.58	0.42	671.8	480.4	1152.2
2	6	0.61	0.39	417.1	261.6	678.7
3	1	0.58	0.50	372.2	248.5	620.7
3	2	0.52	0.38	207.7	125.6	333.3
3	3	0.58	0.42	502.3	523.1	1085.4
3	4	0.59	0.41	383.9	271.0	654.9
3	5	0.61	0.39	429.7	273.5	703.3
3	6	0.63	0.37	345.5	206.1	551.6
5	1	0.53	0.37	233.3	138.9	372.2
4	2	0.63	0.37	243.8	142.8	386.4
4	3	0.63	0.37	303.0	180.7	483.7
4	4	0.63	0.37	293.0	170.9	463.9
4	5	0.67	0.33	258.7	129.2	387.9
4	6	0.63	0.37	310.2	185.7	495.9
Date: June 4, 1991						
1	1	0.58	0.42	306.9	221.9	528.8
1	2	0.55	0.45	312.8	259.3	571.1
1	3	0.56	0.44	317.5	258.6	566.0
1	5	0.52	0.58	502.3	542.1	1324.4
1	5	0.55	0.45	651.1	551.2	1212.3
1	5	0.52	0.48	539.1	497.5	1036.6
2	1	0.50	0.50	615.4	813.1	1228.5
2	2	0.51	0.49	591.5	566.0	1157.5
2	3	0.52	0.48	895.9	829.4	1726.3
2	4	0.52	0.48	718.8	557.1	1375.9
2	5	0.51	0.59	775.5	740.4	1516.9
2	6	0.50	0.50	740.7	746.7	1487.4
3	1	0.56	0.44	510.6	502.3	912.9
3	2	0.55	0.45	456.8	375.7	832.5
3	3	0.52	0.48	586.3	536.7	1123.0
3	4	0.51	0.59	757.7	733.5	1501.2
3	5	0.53	0.57	677.9	512.5	1290.5
3	6	0.52	0.48	458.5	423.7	882.2
4	1	0.55	0.45	413.4	335.0	758.5
4	2	0.55	0.45	296.1	238.2	535.3
4	3	0.54	0.46	357.0	301.9	658.9
4	4	0.56	0.44	424.7	335.2	759.9
4	5	0.54	0.46	599.5	501.0	1100.5
4	6	0.59	0.41	258.3	178.4	436.7

Table A.2 continued.

Rep	Trt	Fraction leaf	Fraction stem	Leaf dry wt.	Stem dry wt.	Total dry wt.
				---------- Kg ha^{-1} ----------		
Date : June 11, 1991						
1	1	0.49	0.51	576.4	633.5	1168.9
1	2	0.55	0.45	234.8	189.5	424.3
1	3	0.52	0.48	372.4	346.5	718.9
1	4	0.54	0.46	414.1	352.5	766.6
1	6	0.62	0.38	1661.6	1488.9	3550.5
1	6	0.46	0.46	949.8	1123.4	2873.2
2	1	0.49	0.51	862.9	878.2	1731.1
2	2	0.48	0.52	927.6	999.6	1927.2
2	3	0.49	0.51	1071.3	1110.7	2182.0
2	4	0.46	0.54	1294.6	1524.9	2819.5
2	5	0.46	0.66	1695.7	1803.8	3299.5
2	6	0.58	0.42	986.3	1059.6	2043.9
3	1	0.60	0.60	672.6	566.0	1138.6
3	2	0.47	0.53	789.9	806.8	1616.7
3	3	0.50	0.50	563.8	573.2	1137.0
3	4	0.50	0.50	943.7	948.7	1892.4
3	5	0.46	0.54	974.2	1159.8	2134.0
3	6	0.41	0.69	1041.1	1497.6	2538.7
4	1	0.51	0.49	660.8	638.7	895.6
4	2	0.42	0.58	561.4	508.8	1050.2
4	3	0.54	0.46	312.1	267.0	679.1
4	4	0.48	0.52	1196.2	1300.3	2496.5
4	6	0.67	0.53	1863.0	1170.5	2213.5
4	6	0.52	0.48	488.0	447.6	936.6
Date: June 18, 1991						
1	1	0.43	0.57	1273.8	1667.0	2940.0
1	2	0.56	0.44	326.7	254.9	581.6
1	3	0.49	0.51	696.3	725.6	1421.9
1	4	0.33	0.67	1901.4	3811.4	5712.8
1	5	0.60	0.60	976.8	971.6	1947.3
1	6	0.46	0.66	989.1	1227.6	2216.6
2	1	0.39	0.61	1022.8	1601.0	2623.8
2	2	0.37	0.63	1306.7	2236.6	3542.3
2	3	0.39	0.61	1237.3	1976.2	3211.5
2	4	0.34	0.66	1888.1	3696.0	5582.1
2	5	0.32	0.68	1301.6	2761.2	6062.7
2	6	0.37	0.63	1972.8	3316.0	6287.8
3	1	0.66	0.64	936.3	1116.5	2052.8
3	2	0.46	0.66	721.7	901.2	1622.9
3	3	0.47	0.63	790.1	903.5	1693.6
3	4	0.36	0.66	1538.9	2866.4	4405.3
3	5	0.66	0.64	1336.4	1555.7	2891.1
3	6	0.42	0.58	728.6	1012.9	1741.5
4	1	0.60	0.60	958.9	958.4	1917.3
4	2	0.63	0.47	644.3	582.9	1227.2
4	3	0.54	0.46	568.1	492.8	1060.9
4	4	0.36	0.66	1127.8	2177.2	3306.2
4	5	0.44	0.56	1349.2	1722.3	3071.6
4	6	0.49	0.51	673.2	706.9	1380.1

Table A.2 continued.

Rep	Trt.	Fraction leaf	Fraction stem	Fraction panicle	Leaf dry wt.	Stem dry wt	Panicle dry wt	Total dry wt.
					kg ha^{-1}			
Date : July 2, 1991								
1	1	0.32	0.58	0.10	753.5	1367.2	247.7	2368.4
1	2	0.35	0.59	0.07	700.9	1178.8	133.9	2013.6
1	3	0.36	0.51	0.13	655.9	930.5	235.5	1821.9
1	4	0.26	0.59	0.15	1081.2	2407.2	639.3	4207.7
1	5	0.28	0.53	0.18	1273.9	2423.1	834.0	4531.0
1	6	0.24	0.52	0.24	1121.9	2415.5	1194.4	4631.9
2	1	0.28	0.61	0.11	770.7	1684.7	291.0	2746.4
2	2	0.25	0.56	0.19	1015.8	2247.0	778.8	4041.6
2	3	0.26	0.56	0.18	1198.3	2571.8	835.9	4606.0
2	4	0.22	0.49	0.29	1332.4	3010.3	1773.8	6115.7
2	5	0.25	0.58	0.25	1637.4	3229.5	1586.2	6453.1
2	6	0.32	0.54	0.14	1351.6	2253.2	563.7	4168.5
3	1	0.28	0.57	0.14	990.3	1999.0	500.3	3489.6
3	2	0.33	0.57	0.10	976.1	1701.1	302.7	2979.8
3	3	0.29	0.59	0.12	1108.7	2244.5	472.6	3825.8
3	4	0.21	0.56	0.23	769.6	2064.5	851.9	3686.0
3	5	0.27	0.53	0.20	1164.8	2296.1	873.0	4333.1
3	6	0.30	0.57	0.13	1376.6	2643.8	609.7	4630.1
4	1	0.33	0.57	0.10	927.8	1602.8	279.7	2809.5
4	2	0.34	0.53	0.12	663.2	1029.4	233.5	1926.1
4	3	0.33	0.57	0.10	916.6	1583.8	279.3	2779.7
4	4	0.25	0.57	0.18	1317.4	2973.6	947.7	5238.7
4	5	0.31	0.54	0.16	941.9	1654.8	480.7	3077.4
4	6	0.28	0.53	0.19	951.9	1800.1	656.6	3408.7
Date: July 9, 1991								
1	1	0.24	0.56	0.20	1187.5	2573.2	943.2	4623.9
1	2	0.28	0.57	0.14	753.3	1520.9	381.2	2655.4
1	3	0.29	0.55	0.16	653.0	1216.1	353.8	2223.0
1	4	0.16	0.48	0.36	1158.9	3517.9	2612.1	7281.0
1	5	0.26	0.57	0.17	1476.2	3301.3	999.8	5777.3
1	6	0.26	0.51	0.24	1279.6	2524.1	1191.8	4995.5
2	1	0.24	0.52	0.24	857.2	1910.4	878.4	3646.0
2	2	0.22	0.44	0.34	1425.0	2860.6	2233.7	6525.3
2	3	0.29	0.57	0.14	961.2	1901.9	467.0	3330.2
2	4	0.23	0.53	0.24	1120.6	2609.0	1176.8	4906.4
2	5	0.20	0.45	0.35	1283.2	2804.0	2209.8	6297.0
2	6	0.28	0.54	0.18	1288.6	2449.4	826.5	4564.5
3	1	0.24	0.54	0.22	1033.0	2306.5	933.2	4272.7
3	2	0.30	0.55	0.16	742.6	1380.2	391.6	2514.4
3	3	0.24	0.49	0.27	969.2	1970.6	1101.7	4041.5
3	4	0.19	0.56	0.25	1064.1	3152.6	1360.4	5477.0
3	5	0.26	0.53	0.21	1368.6	2778.7	1095.6	5234.9
3	6	0.24	0.43	0.33	1487.8	2692.8	2102.3	6282.1
4	1	0.26	0.60	0.15	905.3	2102.7	516.0	3524.0
4	2	0.32	0.53	0.15	896.4	1499.8	434.4	2830.6
4	3	0.27	0.54	0.19	737.3	1477.3	512.3	2726.9
4	4	0.23	0.51	0.26	808.3	1795.3	909.8	3513.4
4	5	0.25	0.54	0.21	1085.3	2377.1	939.4	4401.9
4	6	0.40	0.46	0.14	881.9	1008.5	315.9	2198.2

Table A 2 continued

Rep.	Trt	Fraction leaf	Fraction stem	Fraction panicle	Leaf dry wt	Stem dry wt	Panicle dry wt	Total dry wt
					kg ha^{-1}			
Date : July 16, 1991								
1	1	0.23	0.48	0.29	723.7	1485.4	889.4	3098.5
1	2	0.22	0.62	0.16	650.1	1838.3	481.7	2970.1
1	3	0.26	0.47	0.27	991.1	1826.2	1063.7	3881.0
1	4	0.16	0.36	0.48	1116.5	2502.5	3426.9	7045.9
1	5	0.18	0.35	0.47	1156.8	2169.1	2946.1	6272.0
1	6	0.26	0.38	0.36	1298.7	1870.5	1750.7	4919.9
2	1	0.23	0.50	0.27	893.2	1957.9	1071.5	3922.6
2	2	0.19	0.44	0.37	833.6	1925.7	1596.2	4355.5
2	3	0.28	0.47	0.25	1033.7	1719.1	938.2	3691.1
2	4	0.14	0.28	0.58	1037.6	2030.0	4371.2	7438.8
2	5	0.13	0.25	0.62	1465.1	2752.0	6872.1	11089.2
2	6	0.19	0.35	0.46	986.9	1701.6	2265.0	4793.5
3	1	0.21	0.41	0.37	1089.8	2115.6	1967.4	5112.8
3	2	0.24	0.49	0.27	1015.3	2066.9	1142.5	4224.7
3	3	0.25	0.47	0.28	879.4	1658.7	1086.2	3544.3
3	4	0.23	0.43	0.35	1048.2	1960.1	1592.2	4592.5
3	5	0.19	0.33	0.48	1534.1	2640.0	3930.9	8105.0
3	6	0.17	0.29	0.55	824.5	1391.0	2660.9	4876.4
4	1	0.23	0.42	0.35	948.4	1746.9	1469.2	4156.5
4	2	0.21	0.41	0.38	632.0	1209.6	1112.2	2953.8
4	3	0.23	0.54	0.23	593.3	1367.4	580.8	2541.5
4	4	0.25	0.55	0.19	1001.7	2195.5	759.8	3957.0
4	5	0.22	0.37	0.41	1207.2	2037.5	2250.2	5494.9
4	6	0.28	0.48	0.24	960.2	1614.8	795.4	3370.4
Date: July 23, 1991								
1	1	0.18	0.41	0.40	657.1	1441.7	1391.8	3490.6
1	2	0.25	0.49	0.27	737.5	1447.2	791.5	2976.2
1	3	0.23	0.43	0.34	855.2	1595.3	1283.6	3734.1
1	4	0.18	0.40	0.42	1140.5	2624.9	2716.5	6481.8
1	5	0.20	0.40	0.40	1247.1	2536.9	2492.4	6276.4
1	6	0.17	0.29	0.54	1254.5	2205.4	4128.5	7588.4
2	1	0.20	0.39	0.41	1233.6	2456.0	2537.7	6227.3
2	2	0.24	0.49	0.27	1138.3	2375.0	1326.4	4839.6
2	3	0.18	0.35	0.47	1468.6	2894.6	3871.7	8235.1
2	4	0.13	0.32	0.55	1260.0	3030.8	5267.2	9558.0
2	5	0.14	0.29	0.57	1237.0	2588.2	5076.5	8901.7
2	6	0.20	0.33	0.48	1315.9	2189.4	3287.9	6713.3
3	1	0.19	0.41	0.40	993.5	2153.6	2188.9	5245.9
3	2	0.22	0.39	0.40	819.2	1460.8	1498.1	3778.1
3	3	0.20	0.35	0.44	1173.9	2036.7	2562.8	5773.4
3	4	0.17	0.37	0.47	1021.4	2274.3	2887.9	6182.6
3	5	0.15	0.32	0.53	1512.5	3175.1	5209.0	9896.6
3	6	0.20	0.30	0.50	1379.2	2104.4	3540.3	7023.8
4	1	0.22	0.40	0.38	726.6	1331.4	1271.9	3329.9
4	2	0.19	0.40	0.41	548.4	1121.9	1153.3	2815.6
4	3	0.25	0.43	0.33	756.8	1308.9	1007.0	3072.7
4	4	0.14	0.31	0.54	922.0	1992.7	3455.5	6370.2
4	5	0.21	0.40	0.39	899.1	1707.3	1677.0	4283.4
4	6	0.19	0.32	0.48	767.5	1270.0	1901.9	3939.3

Table A-3 Volumetric soil water content at different soil depths in sorghum plots under optimum and rainfed conditions

Date		Soil depth (cm) 23	30	65	82	90
		%				
OPTIMUM IRRIGATION						
May13	0	8.6	9.0	8.6	7.8	6.9
May15	2	7.9	8.5	8.5	7.5	5.9
May25	12	12.0	12.2	10.8	10.0	8.2
May28	15	11.2	11.2	10.2	9.7	8.9
May30	17	11.8	11.3	10.1	9.3	8.7
June1	19	12.8	12.5	11.5	10.8	9.2
June15	32	8.7	8.8	8.5	8.0	8.3
June16	33	9.5	9.6	8.6	7.7	8.1
June18	36	8.5	8.6	8.5	7.7	7.9
June23	41	8.3	8.3	8.1	7.3	5.3
June25	43	7.8	7.8	7.7	7.0	7.3
June30	49	9.0	9.5	8.7	7.9	7.2
July4	53	7.5	8.1	8.1	7.4	7.2
July6	55	9.8	8.8	8.1	7.3	6.3
July8	57	9.2	8.9	7.9	7.3	6.9
July10	59	13.2	13.0	11.1	9.4	6.9
July15	66	9.8	10.2	9.9	8.2	9.7
RAINFED						
May13	0	9.1	9.4	9.0	8.6	9.2
May15	2	8.3	8.7	8.6	7.8	8.0
May25	12	11.8	11.8	11.3	10.5	9.3
May28	15	11.8	11.1	10.3	9.8	9.9
May30	17	11.8	11.4	10.3	9.5	9.7
June1	19	12.6	12.4	11.5	11.1	10.9
June16	32	6.7	7.5	8.3	7.9	8.3
June16	34	5.6	6.8	7.8	7.7	7.8
June18	36	5.2	6.2	7.6	7.5	7.5
June23	41	5.6	6.2	7.1	7.0	7.4
June25	43	5.5	6.1	6.9	6.7	6.7
June30	49	8.8	8.9	8.6	7.7	6.9
July5	53	7.0	7.8	8.1	7.6	6.7
July5	55	6.8	7.3	7.9	7.3	5.6
July8	57	5.1	6.8	7.6	7.0	6.5
July10	59	12.2	12.0	10.3	8.5	6.8
July15	64	9.3	9.9	9.7	8.6	9.2

Table A.4 Amount of NO_3-N at different soil depths in plots under optimum irrigation and 300 kg ha^{-1} of applied N.

Soil depth	Days after planting				
	14	38	50	75	99
cm	ppb				
15	1.66	3.37	1.23	0	0
30	3.52	0.12	3.68	0	0
45	7.24	0.43	3.68	0	0
60	12.39	3.37	0.61	0.61	0
90	9.02	5.4	1.04	1.23	0
	kg N ha^{-1}				
15	3.98	8.10	2.95	0.00	0.00
30	8.74	0.29	9.14	0.00	0.00
45	17.59	1.04	8.94	0.00	0.00
60	29.58	8.04	1.45	1.45	0.00
90	43.62	26.13	5.03	5.95	0.00
0-90	103.53	43.62	27.54	7.408	0.00

Table A.5 Amount of atrazine recovered from different depths of soil over time.

Rep	Trt†	Soil depth	Days after application			
			2	26	39	63
		cm	ppb			
1	1	15	110.73	17.83	15.11	6.83
1	1	30	41.72	0.86	0.00	4.73
1	1	45	5.79	1.83	0.00	4.85
1	1	60	1.70	0.00	0.86	0.99
1	1	90	5.02	0.00	0.00	0.92
1	2	15	38.98	1.84	4.53	8.69
1	2	30	2.47	0.90	5.78	2.78
1	2	45	1.65	0.00	3.59	7.57
1	2	60	0.00	0.00	2.82	1.83
1	2	90	0.86	2.62	2.67	2.55
1	3	15	33.58	0.00	15.88	7.84
1	3	30	5.81	0.00	7.85	0.00
1	3	45	1.78	0.92	3.60	0.00
1	3	60	1.70	0.00	0.86	0.91
1	3	90	4.26	0.00	1.85	0.84
1	4	15	193.07	25.60	8.79	9.23
1	4	30	29.47	4.81	0.00	5.84
1	4	45	12.15	0.82	0.00	1.00
1	4	60	11.77	3.53	2.80	5.65
1	4	90	5.07	0.00	2.75	2.70
1	5	15	172.00	40.75	11.81	8.25
1	5	30	5.28	0.00	2.93	4.36
1	5	45	15.86	0.00	3.67	4.26
1	5	60	2.68	0.90	2.65	3.42
1	5	90	5.20	0.90	2.85	2.72
1	6	15	199.90	27.02	8.37	9.01
1	6	30	10.71	1.80	6.58	0.91
1	6	45	12.73	2.71	4.88	0.00
1	6	60	3.82	0.00	1.77	1.60
1	6	90	0.85	0.91	5.34	0.00
2	1	15	156.87	17.10	4.46	9.69
2	1	30	8.52	1.87	2.68	5.39
2	1	45	10.00	5.99	4.69	5.62
2	1	60	8.56	0.91	1.82	5.83
2	1	90	5.60	5.43	1.73	14.26
2	2	15	106.45	12.16	9.06	6.34
2	2	30	12.65	4.43	6.07	0.00
2	2	45	9.94	2.65	4.41	3.76
2	2	60	4.70	1.85	1.67	2.40

† 1=optimum irrig x 100 kg N ha^{-1}, 2=optimum irrig x 100 kg N ha^{-1},3=rainfed x 100 kg N ha^{-1}, 4=optimum irrig x 300 kg N ha^{-1}),5=optimum irrig x 300 kg N ha^{-1}, 6=rainfed x 300 kg N ha^{-1}

Table A.5 continued.

Rep	Trt.	Soil depth	Days after application			
			2	26	39	63
		cm	ppb			
2	2	90	5.65	4.66	6.32	0.00
2	3	15	115.07	6.14	4.77	5.88
2	3	30	21.92	0.00	6.39	7.57
2	3	45	9.22	0.89	5.53	11.02
2	3	60	14.51	1.92	1.83	2.62
2	3	90	6.69	1.83	2.63	0.78
2	4	15	.	23.84	0.00	8.16
2	4	30	.	0.96	0.92	2.50
2	4	45	.	0.00	1.86	5.19
2	4	60	.	0.93	4.56	4.24
2	4	90	.	2.71	2.87	5.22
2	5	15	.	35.32	4.90	8.39
2	5	30	.	1.83	2.76	3.47
2	5	45	.	0.00	4.84	3.60
2	5	60	.	0.00	1.91	8.59
2	5	90	.	3.40	2.69	4.79
2	6	15	105.26	8.80	10.69	5.24
2	6	30	5.21	6.76	3.53	2.75
2	6	45	13.54	2.69	7.99	0.00
2	6	60	10.53	1.95	4.49	0.00
2	6	90	5.31	1.80	2.39	0.00
3	1	15	82.39	41.25	9.43	17.82
3	1	30	9.20	8.72	4.13	8.18
3	1	45	10.20	13.98	5.02	12.75
3	1	60	4.22	5.62	1.92	16.02
3	1	90	8.17	6.40	5.69	18.39
3	2	15	118.54	34.95	6.46	31.15
3	2	30	8.61	6.21	10.24	7.56
3	2	45	6.54	5.12	2.76	5.32
3	2	60	9.56	3.91	5.25	6.48
3	2	90	6.27	9.66	2.72	5.78
3	3	15	98.05	16.20	9.45	0.00
3	3	30	31.78	6.85	4.82	3.32
3	3	45	10.07	2.79	7.08	5.50
3	3	60	3.57	5.48	6.33	2.52
3	3	90	4.41	7.39	8.70	4.65
3	4	15	86.34	25.85	9.29	12.98
3	4	30	25.87	2.80	0.00	3.32
3	4	45	13.50	4.53	2.55	1.70
3	4	60	8.62	3.76	0.86	1.61

Table A.5 continued.

Rep	Trt.	Soil depth	Days after application			
			2	26	39	63
		cm	ppb			
3	4	90	9.14	2.78	0.00	3.35
3	5	15	109.93	18.34	9.72	11.71
3	5	30	21.49	15.50	6.20	4.07
3	5	45	12.83	5.72	6.85	4.04
3	5	60	6.05	6.95	3.43	4.48
3	5	90	4.38	7.91	6.94	3.23
3	6	15	121.04	50.10	0.93	6.41
3	6	30	25.40	15.91	1.84	5.04
3	6	45	8.25	5.28	2.83	3.52
3	6	60	1.77	4.41	0.89	5.07
3	6	90	6.00	3.62	0.88	2.67
4	1	15	152.06	8.39	16.51	14.58
4	1	30	61.26	0.00	11.54	14.77
4	1	45	43.08	0.98	1.89	8.24
4	1	60	27.35	0.89	3.95	7.70
4	1	90	9.49	0.00	4.70	7.56
4	2	15	111.55	32.87	4.94	9.89
4	2	30	40.34	0.90	3.59	5.99
4	2	45	19.90	0.00	2.00	7.55
4	2	60	6.93	0.00	3.39	9.08
4	2	90	5.79	1.73	3.92	6.56
4	3	15	136.82	12.49	19.56	4.29
4	3	30	15.36	1.90	10.07	3.11
4	3	45	13.21	0.00	6.06	4.38
4	3	60	6.76	0.00	5.74	6.10
4	3	90	0.89	0.96	7.59	5.96
4	4	15	94.20	29.95	21.19	12.99
4	4	30	4.47	0.90	13.07	10.16
4	4	45	0.00	0.89	8.29	4.58
4	4	60	0.00	0.91	7.80	5.83
4	4	90	0.84	0.00	3.31	3.91
4	5	15	83.22	6.14	7.45	5.67
4	5	30	20.36	0.93	7.10	2.70
4	5	45	16.44	0.00	12.56	3.43
4	5	60	7.88	0.00	5.58	0.00
4	5	90	3.93	0.00	10.48	4.74
4	6	15	193.22	6.71	31.53	1.62
4	6	30	69.43	0.00	19.57	3.06
4	6	45	50.97	0.00	7.61	1.67
4	6	60	19.43	0.00	8.61	0.00
4	6	90	10.31	0.00	5.94	0.83

APPENDIX B

MODEL INPUT DATA FILES

Table B.1 Input data file for LEACHW, the water version of LEACHM

```
WATER      < DOS Filename: 8 characters with no extension. Used in batch runs
(started as LEACHW<filename)
-------------------------------------------------------------------------------
                        LEACHW WATER FLOW DATA FILE
All numeric data are in positions 1 to 78. Comments may extend to position 120
Unless defined as "must read" a value must be present for each item, although it
may not be used.
Free format with blank delimiters.  Preserve division and heading records.  No
of depth segments may be changed
*******************************************************************************
 1       <Date format (1: month/day/year;  2: day/month/year).  Datum must be 6
digits, 2 each for day, mo, yr
 050191  <Starting date.  No data in the input data should precede this date
 072091  <Ending date or day number.  The starting date is day 1  (A value
<010101 is treated as a day number)
 0.0416  <Largest time interval within a day (0.1 day or less).
 0.01    <Maximum water flux per time step  (Dimensionless: flux (mm)/segment
thickness (mm)
 1       <Number of repetitions of rainfall, crop and chemical application data
 900     <Profile depth (mm), preferably a multiple of the segment thickness.
 50      <Segment thickness (mm).  (The number of segments should be between
about 9 and 30.
 2       <Lower boundary condition: 1:fixed depth water table; 2:free drainage,
3:zero flux 4:lysimeter
 9999    <If the lower boundary is 1 or 5: initial water table depth (mm)
*******************************************************************************
******
*******************************************************************************
******
 3       <Number of output files: 1: OUT only; 2: OUT + SUM; 3: OUT + SUM + BTC
------
--- For the *.OUT file :
 1       <Units for depth data: 1: mg/kg, 2: mg/m2 per segment   (Not used in
LEACHW)
 1       <Mode print frequency (print data for every mode (1), alternate modes
(2).
 2       <Print options: 1: 2 or 3.  To select one of the following 3 options
 1       <Option 1: Time steps/print (these are not of equal length)
 1.00    <Option 2: Print at fixed time intervals (days between prints)
 2       <Option 3: No. of prints (the times for which are specified below)
 3       <Tables printed: 1: mass balance; 2: + depth data; 3: + crop data
-------------------------------------------------------------------------------
--- For the *.SUM file :
 1.00    <Summary print interval (d)
 000     <Surface to [depth 1?] mm       (Three depth segments for the
 000     <Depth 1 to [depth 2?] mm        summary file.  Zero defaults to nodes
 000     <Depth 2 to [depth 3?] mm        closest to thirds of the profile)
-------------------------------------------------------------------------------
--- For the *.BTC (breakthrough) file :
 1.0     <Incremental depth of drainage water per output (mm)
-------------------------------------------------------------------------------
-- List here the times at which the *.OUT file is desired for print option 3
-- The number of records must match the No. of prints under option 3 above
        Date or      Time of day          (At least one must be specified
        day no.  (to nearest tenth)        even if print option is not 3)
        --------  ------------------
        052091          .5          (These dates can be past the last day)
        060791          .5
*******************************************************************************
```

Table B 1 continued...

```
**********************************************************************
                    SOIL PHYSICAL PROPERTIES
----------------------------------------------------------------------
-- Retentivity model 0 uses fitted Campbell's retention parameters, otherwise
-- the desired particle size-based regression model (Table 2.1 in manual) is
used.
----------------------------------------------------------------------
| Soil layer no. | Clay | Silt | Organic carbon | Retention model | Starting theta or psi (same is used) | Roots (for no growth) (relative) | Starting temp (C) (not used in LEACHEW,C) |
|                | %    | %    | %              |                 | kPa                                  |                                  |                                           |
|----------------|------|------|----------------|-----------------|--------------------------------------|----------------------------------|-------------------------------------------|
| 1              | 16.  | 10.  | 2.0            | 0               | .052                                 | -15.00                           | .01                                       | 20.                                       |
| 2              | 16.  | 10.  | 2.0            | 0               | .052                                 | -15.00                           | .05                                       | 20.                                       |
| 3              | 16.  | 10.  | 2.0            | 0               | .052                                 | -15.00                           | .05                                       | 20.                                       |
| 4              | 16.  | 10.  | 1.0            | 0               | .083                                 | -9.80                            | .05                                       | 20.                                       |
| 5              | 16.  | 10.  | 1.0            | 0               | .083                                 | -9.80                            | .10                                       | 20.                                       |
| 6              | 16.  | 10.  | 1.0            | 0               | .083                                 | -9.80                            | .10                                       | 20.                                       |
| 7              | 16.  | 10.  | 0.5            | 0               | .080                                 | -9.80                            | .10                                       | 20.                                       |
| 8              | 16.  | 10.  | 0.5            | 0               | .080                                 | -9.80                            | .10                                       | 20.                                       |
| 9              | 16.  | 10.  | 0.5            | 0               | .080                                 | -9.80                            | .10                                       | 20.                                       |
| 10             | 16.  | 10.  | 0.0            | 0               | .080                                 | -9.80                            | .05                                       | 20.                                       |
| 11             | 16.  | 10.  | 0.0            | 0               | .080                                 | -9.80                            | .05                                       | 20.                                       |
| 12             | 16.  | 10.  | 0.0            | 0               | .080                                 | -9.80                            | .05                                       | 20.                                       |
| 13             | 16.  | 10.  | 0.0            | 0               | .079                                 | -7.80                            | .05                                       | 20.                                       |
| 14             | 16.  | 10.  | 0.0            | 0               | .075                                 | -7.80                            | .05                                       | 20.                                       |
| 15             | 16.  | 10.  | 0.0            | 0               | .079                                 | -7.80                            | .05                                       | 20.                                       |
| 16             | 16.  | 10.  | 0.0            | 0               | .079                                 | -7.80                            | .01                                       | 20.                                       |
| 17             | 16.  | 10.  | 0.0            | 0               | .079                                 | -7.80                            | .01                                       | 20.                                       |
| 18             | 16.  | 10.  | 0.0            | 0               | .075                                 | -7.80                            | .01                                       | 20.                                       |
----------------------------------------------------------------------
   1    < Use listed water contents (1) or potentials (2) at starting values
Particle density:  Clay     Silt and sand     Organic matter  (kg/dm3) (to
calculate porosity)
                  2.65              2.65              1.10
**********************************************************************
For a uniform profile: Any non-zero value here will overrride those in
the table below (only if retentivity model is 0)...
----------------------------------------------------------------------
   0.0        <Soil bulk density (kg/dm3)
  -0.00       < Air-entry value' (AEV) (kPa) (a in eq 2.1 to 2.4)
   0.00       <Exponent (BCAH) in Campbell's water retention equation (b in eq
2.1 to 2.4)
   0000   -9.0  <Conductivity (mm/day) and corresponding matric potential (kPa)
(for potential-based version of eq 2.5)
   0.0        <Pore interaction parameter (F) in Campbell's conductivity
equation (eq 2.5 in manual)
   0          <Dimpermivity (mm) (eq  3.12).  (Read, but not used in LEACHW)
**********************************************************************
| Soil management no. | Soil retentivity parameters | | Bulk density | Match K(h) curve at: | | Dimpermivity (not read in LEACHW) |
|                     | AEV kPe | BCAH | kg/dm3 | K mm/d | Matric pot. kPa | theta | mm |
|---------------------|---------|------|--------|--------|-----------------|-------|----|
| 1 | -1.42 | 0.98 | 1.603 | 5062.4 | -0.0 | 1.0 | 100. |
| 2 | -1.42 | 0.98 | 1.603 | 5062.4 | -0.0 | 1.0 | 100. |
| 3 | -1.42 | 0.98 | 1.603 | 5062.4 | -0.0 | 1.0 | 100. |
| 4 | -1.45 | 0.98 | 1.657 | 5383.2 | -0.0 | 1.0 | 100. |
| 5 | -1.45 | 0.98 | 1.657 | 5383.2 | -0.0 | 1.0 | 100. |
| 6 | -1.45 | 0.98 | 1.657 | 5383.2 | -0.0 | 1.0 | 100. |
| 7 | -1.15 | 1.018 | 1.021 | 6692.8 | -0.0 | 1.0 | 100. |
| 8 | -1.10 | 1.018 | 1.021 | 5692.8 | -0.0 | 1.0 | 100. |
| 9 | -1.19 | 1.018 | 1.021 | 6692.8 | -0.0 | 1.0 | 100. |
| 10 | -1.22 | 0.853 | 1.592 | 7074.4 | -0.0 | 1.0 | 100. |
| 11 | -1.22 | 0.853 | 1.592 | 7074.4 | -0.0 | 1.0 | 100. |
| 12 | -1.22 | 0.853 | 1.592 | 7074.4 | -0.0 | 1.0 | 100. |
```

Table E 1 continued

13	-1.3	0.823	1.400	7797.0	-0.0	1.0	100
14	-1.3	0.823	1.000	7797.6	-0.0	1.0	100
15	-1.3	0.823	1.400	7797.6	-0.0	1.0	100
16	-1.62	0.775	1.613	7965.6	-0.0	1.0	100
17	-1.62	0.775	1.613	7965.0	-0.0	1.0	100
18	-1.62	0.775	1.613	7965.6	-0.0	1.0	100

****

****

CROP DATA

Data for at least one crop must be specified, even if no crop desired. For fallow soil, set flag below to 0. If germination past the simulation end date.

1 <Plants present: 1 yes, 0 no. This flag overrides all other crop data.
1 <Number of crops (>0), even if bypassed. Dates can be past last day of simulation.
1 <Growth: 1:Wo(use root data specified above, crop cover below); 2:Yes.
-1500 <Wilting point (soil) kPa
-3000 <Minimum water pot if(kpa)
1.0 <Maximum ratio of actual to potential transpiration (dry surface)
1.05 <Root resistance (weights water uptake by depth). (>1. No weighting;
1.0). See Eq. 2-18.

Crop #	Germination date	Emergence date	Maturity date	Harvest date	Kcl-root	Crop cover	Pan factor	Annual N uptake kg/ha
LEACHN only)			Root depth	Plant depth				
1	050101	050201	060301	071591	072091	0.90	0.0	0.0	102

****

****

RAIN/IRRIGATION AND WATER COMPOSITION

Choosing the steady-state flow option will prevent salts in the water flow subroutine, fix fluxes and concentrations at those specified below and maintain them constant with time. Interrupted steady-state can be specified by appropriate times and amounts. For the steady-state flow option, use a uniform soil column.

1	< Water flow: Richards (1), modified Addiscott (2), steady-state (3)
-5	< For Addiscott : matric potential at field capacity (kPa).
-200	< : division between mobile and immobile water (kPa)
0.4	< For steady-state: Water content in uniform column (theta)
40	< Number of water applications. Some or all can be past last day

---

Start time Date or Day no.	Time of day	Amount mm	Surface flux density cm/d	Dissolved in water (can be 0) Chem1 (not read or used in LEACHN)	Chem2	Chem3	Chem4
050101	08.0	07.0	200.0	0.000E+00	0.000E+00	0.000E+00	0.000E+00
050791	07.0	02.0	200.0	0.000E+00	0.000E+00	0.000E+00	0.000E+00
051101	04.0	13.0	200.0	0.000E+00	0.000E+00	0.000E+00	0.000E+00
051891	21.0	14.0	200.0	0.000E+00	0.000E+00	0.000E+00	0.000E+00
051991	05.0	21.0	200.0	0.000E+00	0.000E+00	0.000E+00	0.000E+00
052091	05.0	1.0	200.0	0.000E+00	0.000E+00	0.000E+00	0.000E+00
052391	00.0	9.0	200.0	0.000E+00	0.000E+00	0.000E+00	0.000E+00
052491	17.0	20.0	200.0	0.000E+00	0.000E+00	0.000E+00	0.000E+00
052691	042.0	11.0	200.0	0.000E+00	0.000E+00	0.000E+00	0.000E+00
052791	075.0	8.0	200.0	0.000E+00	0.000E+00	0.000E+00	0.000E+00
052991	075.0	14.0	200.0	0.000E+00	0.000E+00	0.000E+00	0.000E+00

Table 8.1 continued.

032191	2	19.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
060491	.542	9.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
060591	92	50.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
060691	.063	15.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
060791	.375	9.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
061291	.333	17.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
061391	.333	9.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
061791	.667	3.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
061991	.42	9.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
062191	.222	19.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
062291	.625	3.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
062291	625	1.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
062491	625	7.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
062391	.01	1.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
062891	.623	21.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
062791	.63	1.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
062991	.75	4.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
062091	625	2.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
070191	.67	3.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
070691	70	7.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
070891	.652	2.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
070991	.50	26.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
071191	37	20.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
071291	75	2.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
071491	43	1.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
071691	32	3.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
071791	.05	30.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
071991	.46	39.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
072091	33	1.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
072291	445	1.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
072491	56	1.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
072591	.65	1.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
072691	33	16.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
072891	48	16.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
072991	55	12.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
073091	25	3.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
072191	36	29.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00

****

POTENTIAL ET (WEEKLY TOTALS, mm) DEPTH TO WATER TABLE (mm)
MEAN WEEKLY TEMPERATURES AND MEAN WEEKLY AMPLITUDE (degrees C)

Week no.	ET	Water table	Mean temp	Amplitude
1	40.6	0.	25.2	7.1
2	28.5	0.	25.7	6.0
3	41.4	0.	26.3	5.0
4	28.2	0.	26.0	4.5
5	40.1	0.	26.6	6.2
6	37.3	0.	22.3	3.9
7	49.5	0.	26.9	7.1
8	44.9	0.	28.1	6.3
9	43.4	0.	27.7	5.0
10	44.5	0.	27.9	5.7
11	29.2	0.	27.2	5.3
12	40.9	0.	28.0	6.6
13	23.5	0.	27.4	5.3

```
Table B.2 Input data file for LEACHM, the nitrogen version of LEACHM

BITRATE  < DOS Filename  8 characters with no extension. Used in batch runs
(started as LEACHN<filename).
-------------------------------------------------------------------------------
                    LEACHM NITROGEN DATA FILE
All numeric data are in positions 1 to 78, comments may extend to position 128
Unless defined as 'not read' a value must be present for each item, although it
may not be used.
Free format with blank delimiters.  Preserve division and heading records.  Do
of depth segments may be changed.
*******************************************************************************
 1       <Date format (1: month/day,year; 2: day/month/year)  Dates must be 6
digits, 2 each for day, mm, yr
 050101  <Starting date.  No date is the input date should precede this date.
 071101  <Ending date or day number.  The starting date is day 1.  (A value
<010101 is treated as a day number)
 0 8410  <Largest time interval within a day (0 1 day or less)
 0 01    <Maximum water flux per time step  (Dimensionless: flux (mm)/segment
thickness (mm))
 1       <Number of repetitions of rainfall, crop and chemical application data.
 600     <Profile depth (mm)  preferably a multiple of the segment thickness
 50      <Segment thickness (mm)  (The number of segments should be between
about 8 and 30.)
 2       <Lower boundary condition: 1:fixed depth water table; 2:free drainage,
3:zero flux 4:lysimeter.
 9000    <If the lower boundary is 1 or 5: initial water table depth (mm)
*******************************************************************************
*******************************************************************************
 3       <Number of output files: 1: OUT only; 2: OUT + SUM; 3: OUT + SUM + BTC
-------------------------------------------------------------------------------
--- For the * OUT file :
 1       <Units for depth data: 1: mg/kg, 2: mg/m2 per segment  (Not used in
LEACHM)
 1       <Node print frequency (print data for every node (1), alternate nodes
(2))
 2       <Print options: 1, 2 or 3.  To select one of the following 3 options.
 1       <Option 1: Time steps/print (these are not of equal length)
1.00     <Option 2: Print at fixed time intervals (days between prints)
 2       <Option 3: No. of prints (the times for which are specified below)
 3       <Values printed: 1: mass balance; 2: + depth data; 3: + crop data
-------------------------------------------------------------------------------
--- For the * SUM file :
1.00     <Summary print interval (d)
 600     <Surface to (depth 1?) mm       ( Three depth segments for the
 600     <Depth 1 to (depth 2?) mm        summary file.  Zero defaults to nodes
 600     <Depth 2 to (depth 3?) mm        closest to thirds of the profile)
-------------------------------------------------------------------------------
--- For the * BTC (breakthrough) file :
2.0      <Incremental depth of drainage water per output (mm)
-------------------------------------------------------------------------------
-- List here the times at which the *.OUT file is desired for print option 3
-- The number of records must match the No. of prints under option 3 above.
        Date or    Time of day              (At least one must be specified
        Day no.  (th nearest tenth)          even if print option is not 3)
        --------  ------------
        052091          ,5          (These dates can be past the last day)
        060791          ,5
*******************************************************************************
*******************************************************************************
                    SOIL PHYSICAL PROPERTIES
-------------------------------------------------------------------------------
-- Retentivity model 0 uses listed Campbell's retention parameters, otherwise
-- the desired particle size-based regression model (Table 2.1 in manual) is
used.
```

Table B.2 continued

Soil layer no	Clay %	Silt %	Organic carbon %	Retention model	Starting theta or pot (one is used)	Roots (for me growth) (relative)	Starting temp (C) (not read in LEACHW.C)
1	10	10	2 0	0	.652	-15 00	92	20
2	10	10	2 0	0	852	-15.00	05	20
3	10	10.	2 0	0	952	-15.00	05	20
4	10	10	1.0	0	883	-5 00	05	20
5	10	10.	1 0	0	883	-5 00	.10	20
6	10	10	1 0	0	883	-5 00	10	20
7	10	10	0 5	0	000	-5 00	.10	20
8	10	10	0.5	0	000	-5 00	10	20
9	10	10	0.5	0	.000	-5 00	10	20
10	10	10	0 0	0	000	-5 00	05	20
11	10	10	0.0	0	000	-5 00	05	20
12	10	10	0.0	0	000	-5 00	.05	20
13	10	10	0.0	0	070	-7.00	05	20
15	10	10	0.0	0	075	-7.00	.05	20
15	10	10	0.0	0	070	-7 00	05	20
16	10	10	0 0	0	075	-7 00	.01	20
17	10	10	0 0	0	070	-7 00	01	20
18	10	10	0 0	0	075	-7 00	01	20

2 < Use listed water contents (1) or potentials (2) as starting values
Particle density: Clay Silt and sand Organic matter (kg/dm3) (to calculate porosity)
2.65 2.55 1.10
Use a uniform profile: Any non-zero value here will override those in the table below (only if retentivity model is 0)
0.0 <Soil bulk density (kg/dm3)
-0.00 < Air-entry value' (AEV) (kPa) (n is eq 2-1 to 2-4)
0.00 <Exponent (BCAH) in Campbell's water retention equation (b in eq 2 1 to 2 4(
0000 -0 0 <Conductivity (mm/day) and corresponding matric potential (kPa) (for potential-based version of eq. 2.5(
0-0 <Soil interaction parameter (θ) in Campbell's conductivity equation (eq.2-5 in manual)-
0 <Dispersivity (mm) (eq. 3.12). (Read, but not used in LEACHW(

Soil segment no.	Soil retentivity parameters AEV kPa	BCAH	Bulk density kg/dm3	Hetch K(h) curve st: K Matrix pot'l kPa	Matrix symmetry F	Dispersivity (not read in LEACHW) mm
1	-1.42	0 66	1 803	5052 4 -0.0	1.0	100
2	-1 42	0 66	1 603	5052 4 -0.0	1 0	100
3	-1.52	0.68	1-603	6052 4 -0-0	1.0	100
4	-1.55	0.68	1.657	5383.2 -0-0	1.0	100
5	-1 45	0 58	1 657	5363 2 -0.0	1.0	100
6	-1 45	0 58	1 557	5363 2 -0-0	1-0	100
7	-1 15	1 018	1 521	5052 8 -0-0	1.0	100
8	-1-16	1-018	1 621	5052 8 -0 0	1 0	100
6	-1 15	1.018	1-621	6002-9 -0-0	1-0	100
10	-1 22	0 853	1 562	7074 4 -0-0	1.0	100
11	-1 22	0 853	1 552	7074 4 -0-0	1 0	100
12	-1 22	0 853	1 552	7074 4 -0-0	1.0	100
13	-1-3	0-823	1-600	7757 5 -0-0	1 0	100
14	-1.3	0-823	1-600	7757-6 -0-0	1.0	100
15	-1 3	0 823	1 600	7757.5 -0-0	1.0	100
15	-1 42	0.775	1 513	7665 6 -0 0	1 0	100
17	-1 42	0.775	1 613	7965.6 -0-0	1.0	100
18	-1 42	0-775	1 513	7665.6 -0-0	1 0	100

Table B-2 continued

```
**********************************************************************
                          CROP DATA
----------------------------------------------------------------------
  Data for at least one crop must be specified  even if no crop desired
  For fallow soil, set flag below to 0, or germination past the simulation end
  date.
----------------------------------------------------------------------
1       <Plants present: 1 yes, 0 no   This flag overrides all other crop data
1       <No. of crops (>0), even if bypassed.  Dates can be past last day of
simulation.
1       <Growth: 1:No(use root data specified above, sprog covar below); 2:Yes
-1300   <Wilting point (soil) kPa
-3000   <Min root water pot'l(kPa)
1.1     <Maximum rmtio of actual to potential transpiration (dry surface)
1.05    <Root resistance (weights water uptake by depth)  (>1, No weighting;
1.0)  See Eq. 2-16
----------------------------------------------------------------------
Crop Germination Emergence  Maturity     Harvest Rel.  Crop      Pan     Annual
(read in                          Root  Plant                 root  cover   factor   N uptake
 no                                                        depth fraction          ) kg/ha
LEACHN
 ------- Date or Day no. -------                                                   only)
  1    850101    850501  851031  872501  875101  0.00   0.75   0.0      102
**********************************************************************
**********************************************************************
                  INITIAL NITROGEN AND CARBON IN PROFILE
----------------------------------------------------------------------
                  NITROGEN POOLS                    CARBON POOLS
SOIL      UREA  NH4     NO3 Litter  Humus Manure  Litter  Humus Manure
LAYER          ----mg/kg dry soil----              -mg/kg dry soil-
------------------------------------------------------------------------
  1      0.0   0.0     1.00   00     000    000     0000    00     0.0
  2      0.0   0.0     1.00   00     000    0.0     000     00     0.0
  3      0.0   0.0     1.06   00     000    0.0     000     00     0.0
  4      0.0   0.0     5.52   00     000    0.0     000     00     0.0
  5      0.0   0.0     5.52   00     000    0.0     000     00     0.0
  6      0.0   0.0     3.52   00     000    0.0     000     00     0.0
  7      0.0   0.0     7.24   00     000    0.0     000     00     0.0
  8      0.0   0.0     7.24   00     000    0.0     000     00     0.0
  9      0.0   0.0     7.24   00     000    0.0     000     00     0.0
 10      0.0   0.0    12.39   00     000    0.0     000     00     0.0
 11      0.0   0.0    12.39   00     000    0.0     000     00     0.0
 12      0.0   0.0    12.58   00     000    0.0     000     00     0.0
 13      0.0   0.0     0.02   00     000    0.0     000     00     0.0
 14      0.0   0.0     0.02   00     000    0.0     000     00     0.0
 15      0.0   0.0     0.02   00     000    0.0     000     00     0.0
 16      0.0   0.0     0.02   00     000    0.0     000     00     0.0
 17      0.0   0.0     0.02   00     000    0.0     000     00     0.0
 18      0.0   0.0     0.02   00     000    0.0     000     00     0.0
----------------------------------------------------------------------
Concentration (mg/l) below profile, used with lower boundaries 1 or 5
                  0.0       0.0       (NH4 and NO3)
 000     < Depth (cm) of water in mixing cell (boundaries 1 and 5 only)  Enter 0
for no mixing cell
**********************************************************************
```

Table 2-2 continued

```
*************************************************************************
   CHEMICAL PROPERTIES                 (Species number refers to the subscript in the
   -------------------                 code, which is not necessarily the order in
                                       which they appear in input and output files.
                          mol          Do not change this order.  The name of a
          Name            i/kg         pool can be changed eg Manure to Faeces, but
   ---------------------- ------       not its concept.  The names between the quotes
   1  UREA-N'             1000e+01     are the names that will be used in the output.)
   2  NH4-N'              3000E+0i     If a tracer is needed, use the first chemical
   3  NO3-N'              00005+00     (UREA).  Set its Rd to 0 and the urea hydrolysis
   4  LITTER-N'                        rate constant to 0.
   5  HUMUS-N'
   6  MANURE-N'
   7  LITTER-C'
   8  HUMUS-C'
   9  MANURE-C'
   10 CH2-C'
-------------------------------------------------------------------------
Diffusion and dispersion coefficients: (see pages 2-5 to 2-7 in manual)
-------------------------------------------------------------------------
  120      <Molecular diffusion coefficient in water (mm2/day)
  0.05i    <Adjustment in Kreisler D equation (a in equation 3-10 (var-3)
  10       <Adjustment in Kreisler D equation (b in equation 3-10)
*************************************************************************
                NITROGEN TRANSFORMATIONS (see Manual (var-3), Section 4-i)
-------------------------------------------------------------------------
    0.5    <Synthesis efficiency factor
    0.2    <Humification fraction.
   10.0    <C/N ratio:Biomass and humus.
Temperature and water content adjustments
      1    <Temperature subroutine? yes(1), no(0)
     20    <Base temperature: at which rate constants below apply
      3    <Q10: factor by which rate constant changes per 10 C increase.
     98    <High end of optimum water content range: air-filled porosity.
   -300    <Lower end of optimum water content: matric potential kPa.
  -1500    <Minimum matric potential for transformations kPa.
    0.4    <Relative transformation rate at saturation (not denitrification)
*************************************************************************
        RATE CONSTANTS  (day ** -1) (All rate constants may vary with depth)
-------------------------------------------------------------------------
          Urea hydr NH4->NO3 NO3->N                Mineralization
Layer     ========= ======== ======                ==============
                                                   Litter    Manure    Humus
=====     ========= ======== ======                ======    ======    =====
  1       .3400e-0   .200E-0  0.i0e-00             .010e-0   .020e-0   .700e-4
  2       .3400e-0   .200e-0  0.i0e-00             .010e-0   .020E-0   .700E-4
  3       .2400e-0   .200e-0  0.10e-00             .010e-0   .020E-0   .700E-4
  4       .1800e-0   .200e-0  0.10e-00             .010e-0   .020e-0   .700e-4
  5       .i60e-0    .200e-0  0.10e-00             .010e-0   .020e-0   .700H-4
  6       .1600e-0   .200e-0  0 10e-00             .010e-0   .020e-0   .700E-4
  7       .1400e-0   .200e-0  0.10e-00             .010e-0   .020e-0   .700E-4
  8       .1600e-0   .200e-0  0.10e-00             .010e-0   .020e-0   .700H-4
  9       .1600e-0   .200e-0  0.i0e-00             .010e-0   .020e-0   .700E-4
  i0      .1400e-0   .200e-0  0.i0e-00             .010e-0   .020e-0   .700E-4
  ii      .1600e-0   .200e-0  0.10e-00             .010e-0   .020e-0   .700E-4
  i2      .1000e-0   .200e-0  0.10e-00             .010e-0   .020e-0   .700E-4
  13      .1000e-0   .200e-0  0.10e-00             .010e-0   .020e-0   .700E-4
  i4      .1400e-0   .200e-0  0.i0e-00             .010e-0   .020e-0   .700H-4
  i5      .1000e-0   .200e-0  0.10e-00             .010e-0   .020e-0   .700E-4
  i6      .1000e-0   .200e-0  0.10e-00             .010e-0   .020e-0   .700E-4
  17      .1400e-0   .200e-0  0.10e-00             .010e-0   .020e-0   .700E-4
  i8      .1400e-0   .200e-0  0.10e-00             .010e-0   .020e-0   .700E-4
-------------------------------------------------------------------------
Additional rates and constants used for calculating N transformations:
  0.4400   <Ammonia volatilization from the surface  (1/day)
  10.0     <Denitrification half-saturation constant (mg/litre)
   0.0     <Limiting NO3/NH4 ratio in solution for nitrification
*************************************************************************
```

Table B.2 continued

```
**********************************************************************
                  NITROGEN AND CARBON APPLICATIONS
                  --------------------------------
1     < Number of broadcast applications  (At least 1.  Can be past last date
----------------------------------------------------------------------
Date or      Incorp e                 NITROGEN (kg/ha)          |  CARBON (kg/ha)
day no    (segments,      Urea    NH4     NO3  Litter Measure  |  Litter  Measure
-------   must be >0)    -----   -----   -----  -------------  |  ------  -------
 060401         1          0       0      79       0       0        800       00
**********************************************************************
                  RAIN/IRRIGATION AND WATER COMPOSITION
                  ------------------------------------
Choosing the steady-state flow option will prevent calls to the water flow
subroutine, fix fluxes and concentrations
at those specified below and maintain theta constant with time  Interrupted
steady-state can be specified by
appropriate times and amounts.  For the steady-state flow option, use a uniform
soil column.
-----------------------------------------------------------------------
  1     < Water flow: Richards (1), modified Addiscott (2), steady-state (3)
 -9     < For Addiscott : matric potential at field capacity (kPa)
-200    <       "       : division between mobile and immobile water (kPa)
  0.4   < For steady-state: Water content in uniform column (theta)
  40    < Number of water applications.  Seam or all can be past last day.

  Start time      Amount      Surface flux          Dissolved in water (can be 0)
Date or  Time of    mm      density            Urea-N      Ammonium-N  Nitrate-N
Day no    day               mm/d                 mg/l          mg/l        mg/l
------  -------  ------  ------------  ----------  ----------  ----------  ----------
 890601       58    97.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 890761       67    92.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 891191       94    13.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 891691       21    10.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 891891        9    21.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 892091        9     1.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 892261       46    8.0          200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 892461       11    20.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 892691      942    11.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 892791       79     6.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 892891       79    14.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 893191        2    16.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 893491      942     9.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 893991       02    90.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 894661      003    19.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 901361      379     9.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 901761      323    11.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 901961      222     9.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 901791      607     2.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 901941       42     6.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 902161      333    19.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 902361      029     3.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 902361      625     1.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 902461      625     1.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 902561       01     1.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 902661      629    21.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 902791       65     1.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 902991       75     4.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 903081      629     2.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 910191       07     2.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 870691       10     7.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 910591      652     2.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 910961       90    26.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 871061       37    20.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 871261       19     2.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
 871661       45     1.0         200.0    0.000E+00   0.000E+00   0.000E+00   0.000E+00
```

Table E.2 continued

071601	.52	2.0	200.0	0.000E+00	0.000E+00	0.000E+00	0.00E+00
071701	.65	30.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
071801	.48	30.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
071901	.35	1.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
072001	.400	1.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
072401	.00	1.0	300.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
072501	.00	1.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
072601	.00	10.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
072701	.40	14.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
072901	.55	12.0	300.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
073001	.20	1.0	300.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00
073101	.30	20.0	200.0	0.000E+00	0.00E+00	0.00E+00	0.00E+00

POTENTIAL ET (WEEKLY TOTALS, mm) DEPTH TO WATER TABLE (mm)
MEAN WEEKLY TEMPERATURE AND MEAN WEEKLY AMPLITUDE (degrees C)

Week no.	ET	Water table	Mean temp	Amplitude
1	11.66	0.	10.0	0.0
2	14.66	0.	10.2	0.4
3	17.27	0.	10.0	5.0
4	13.67	0.	12.2	5.0
5	17.27	0.	13.1	0.0
6	24.13	0.	10.0	5.0
7	34.29	0.	30.1	3.9
8	27.93	0.	17.4	5.2
9	21.33	0.	18.7	5.4
10	35.56	0.	17.6	0.3
11	23.87	0.	18.5	7.7
12	42.82	0.	21.7	0.1
13	38.11	0.	23.5	3.8
14	00.13	0.	25.2	0.3
15	03.03	0.	22.6	0.0
16	40.13	0.	23.0	4.6
17	33.52	0.	26.0	5.1
18	42.67	0.	26.7	0.2
19	38.61	0.	25.1	3.4
20	41.40	0.	25.6	5.8
21	28.19	0.	26.1	0.1
22	00.13	0.	27.2	0.2
23	37.33	0.	27.0	5.0
24	40.53	0.	28.3	5.8
25	44.45	0.	28.0	0.7
26	03.03	0.	26.7	5.0
27	00.00	0.	27.7	5.5
28	38.21	0.	28.0	5.0
29	00.00	0.	28.6	5.7
30	35.56	0.	28.7	5.0
31	34.03	0.	27.3	0.0
32	41.91	0.	28.2	0.0

Table B 3 Input data file for LEACHP, the pesticide version of LEACHM

ATRAZINE < DOS Filename, @ characters with no extension. Used in batch runs (started as LEACHP<filename(

```
------------------------------------------------------------------------------
                    LEACHP PESTICIDE DATA FILE
All numeric data are in positions 1 to 70; comments may extend to position 120.
Unless defined as  not read  a value must be present for each item, although it
may not be used
Free format with blank delimiters  Preserve division and heading records  No
of depth segments may be changed
*****************************************************************************
  1       <Date format (1: month/day/year;  2: day/month/year)   Dates must be 6
digits, 2 each for day, mn, yr
 050191   <Starting date   No date in the input data should precede this date
 072281   <Ending date or day number   The starting date is day 1   (A value
<211191) is treated as a day number)
  0.0200  <Largest time interval within a day (0.1 day or less)
  0.020   <Maximum water flux per time step   (Dimensionless: flux (mm)/segment
thickness (mm)
  1       <Number of repetitions of rainfall  crop and chemical application data
 900      <Profile depth (mm), preferably a multiple of the segment thickness
 50       <Segment thickness (mm)   (The number of segments should be between
about 5 and 30
  2       <Lower boundary condition: 1:fixed depth water table; 2:free drainage,
3:zero flux 4:hydrostatic
 4499     <If the lower boundary is 2 or 3: initial water table depth (mm(
*****************************************************************************
*****************************************************************************
  2       <Number of output files: 1: OUT only; 2: OUT + SUM; 3: OUT + SUM + ETC
------------------------------------
--- For the * OUT file :
  1       <Units for depth data: 1: mg/kg; 2: mg/m2 per segment   (Not used in
LEACHM)
  1       <Node print frequency (print data for every node (1); alternate nodes
(2)...
  2       <Print options: 1, 2 or 3   To select one of the following 3 options
  1       <Option 1: Time steps/print (these are not of equal length)
 1.00     <Option 2: Print at fixed time intervals (days between prints)
  4       <Option 3: No  of prints (the times for which are specified below)
  3       <Tables printed: 1: mass balance; 2: + depth data; 3: + crop data
------------------------------------
--- For the * SUM file :
 1.00     <Summary print interval (d)
 000      <Surface to (depth 1?) mm       ( Three depth segments for the
 000      <Depth 1 to (depth 2) mm        summary file  Zero defaults to nodes
 000      <Depth 2 to (depth 2) mm        nearest to thirds of the profile(
------------------------------------
--- For the * ETC (breakthrough) file :
 1.0      <Incremental depth of drainage water for output (mm)
------------------------------------
-- List here the times at which the * OUT file is desired for print option 3
-- The number of records must match the No. of prints' under option 3 above.
        Date or    Time of day              (At least one must be specified
        Day No:   (to nearest tenth)         even if print option is not 3)
        ---------  ----------
        020191          .2                (These dates may be past the last day)
        032491          .5
        040491          .2
        070191          .2
*****************************************************************************
```

Table B 3 continued

```
**********************************************************************
                    SOIL PHYSICAL PROPERTIES
----------------------------------------------------------------------
-- Retentivity model 0 uses listed Campbell's retention parameters, otherwise
-- the desired particle size-based regression model (Table 2.1 in manual) is
-- used
----------------------------------------------------------------------
 Soil    Clay    Silt   Organic   Retention   Starting     Roots      Starting
layer              %    matter      model     theta or pot'l (for no   temp (C)
 no      %       %       %                   (one is used)  growth)   (not read in
                                                            (selective) LEACHW,C)
                                                  kPa
---  ---------  ------  --------  ----------  ------------  ---------  ----------
 1      10.0     10.0     2.0         0          -.052       -15.00       .02       20.0
 2      10.0     10.0     2.0         0          -.052       -15.00       .05       20.0
 3      10.0     10.0     2.0         0          -.052       -15.00       .05       20.0
 4      10.0     10.0     1.0         0          -.083       -9.00        .05       20.0
 5      10.0     10.0     1.0         0          -.081       -8.00        .10       20.0
 6      10.0     10.0     1.0         0          -.081       -9.00        .10       20.0
 7      10.0     10.0     0.5         0          -.080       -9.00        .10       20.0
 8      10.0     10.0     0.5         0          -.080       -9.00        .10       20.0
 9      10.0     10.0     0.5         0          -.080       -9.00        .10       20.0
10      10.0     10.0     0.0         0          -.080       -9.00        .05       20.0
11      10.0     10.0     0.0         0          -.080       -9.00        .05       20.0
12      10.0     10.0     0.0         0          -.080       -9.00        .05       20.0
13      10.0     10.0     0.0         0          -.070       -7.00        .05       20.0
14      10.0     10.0     0.0         0          -.070       -7.00        .05       20.0
15      10.0     10.0     0.0         0          -.070       -7.00        .05       20.0
16      10.0     10.0     0.0         0          -.070       -7.01        .01       20.0
17      10.0     10.0     0.0         0          -.070       -7.03        .01       20.0
18      10.0     10.0     0.0         0          -.070       -7.03        .01       20.0
----------------------------------------------------------------------
    2      < Use listed water contents (1) or potentials (2) as starting values
Particle density:  Clay      Silt and sand     Organic matter  (kg/dm3) (to
calculate porosity)
                  2.65          2.85              1.10
**********************************************************************
For a uniform profile: Any non-zero values here will override those in
the table below (only if retentivity model is 0).
----------------------------------------------------------------------
   0.0          <Soil bulk density (kg/dm3)
  -0.80         < Air entry value' (AEV) (kPa) (a in eq 2.1 to 2.8)
   0.00         <Exponent (BCAM) in Campbell's water retention equation (b in eq
2.1 to 2.8)
   0.0     -0.0  <Conductivity (mm/day) and corresponding matein potential (kPa)
(for potential-based version of eq. 2.5)
   0.0          <Pore interaction parameter (P) in Campbell's conductivity
equation (eq 2.5 in manual)
   0            <Dispersivity (mm) (eq 3.12)    (Read, but not used in LEACHW)
**********************************************************************
Soil  | Soil retentivity   |  Bulk   | Match K(h) curve at: |  Dispersivity
segment|     parameters    | density |  K     Matric       |   (not read
 no    |  AEV      BCAM    |         |        pot'l    P    |   in LEACHW)
       |  kPa              | kg/dm3  | mm/d     kPa         |     mm
------ | -------  -------  | ------- | -----  -------  ----- | ------
  1    |  -1.62     0.98   |  1.803  | 6062.4   -0.0   1.0  |  100.0
  2    |  -1.62     0.96   |  1.803  | 6062.4   -0.0   1.0  |  100.0
  3    |  -1.82     0.90   |  1.803  | 6062.8   -0.0   1.0  |  100.0
  4    |  -1.45     0.98   |  1.657  | 5383.2   -0.0   1.0  |  100.0
  5    |  -1.45     0.90   |  1.657  | 5383.2   -0.0   1.0  |  100.0
  6    |  -1.45     0.90   |  1.657  | 5383.2   -0.0   1.0  |  100.0
  7    |  -1.19     1.010  |  1.621  | 6892.8   -0.0   1.0  |  100.0
  8    |  -1.10     1.010  |  1.821  | 6892.8   -0.0   1.0  |  100.0
  9    |  -1.10     1.010  |  1.621  | 6892.8   -0.0   1.0  |  100.0
 10    |  -1.22     0.851  |  1.592  | 7878.8   -0.0   1.0  |  100.0
 11    |  -1.22     0.853  |  1.592  | 7674.4   -0.0   1.0  |  100.0
 12    |  -1.22     0.853  |  1.592  | 7874.8   -0.0   1.0  |  100.0
```

Table B.3 continued

```
 13      -1.3        0.823       1.000    7797.6   -0.0      1.0        100
 14      -1.3        0.823       1.000    7797.8   -0.0      1.0        100
 15      -1.3        0.822       1.405    7797.6   -0.0      1.0        100
 16      -1.42       0.775       1.813    7985.0   -0.0      1.0        100
 17      -1.42       0.775       1.813    7985.0   -0.0      1.0        100
 18      -1.42       0.775       1.813    7985.0   -0.0      1.0        100
*****************************************************************************
*****************************************************************************

                              CROP DATA

-----------------------------------------------------------------------------
  Date for at least one crop must be specified, even if no crop desired
  For fallow soil, set flag below to 0, or germination past the simulation end
  date!
-----------------------------------------------------------------------------
1       <Plants present: 1 yes, 0 no.  This flag overrides all other crop data.
1       <No. of crops (>0), even if bypassed.  Datas can be past last day of
simulation
1       <Growth: 1:Use(max root data specified above, crop cover below); 2:Yes
-1500   <Wilting point (soil) kPa
-3000   <Min root water pot'l(kpa)
1.1     <Maximum ratio of actual to potential transpiration (dry surface)
1.05    <Root resistance (weights water uptake by depth)  (>1, No weighting:
1.0)  See Eqs. 2-19
-----------------------------------------------------------------------------
Crop germination Emergence  Maturity     Harvest Rmi   Crop       Fan      Annual
(rmsd in                              Root  Plant          root  cover    factor | N uptake
LEACHN
                  Date or Day no                         depth fraction            kg/ha
only)
-----------------------------------------------------------------------------
  1       042891      042991   091091 071991   072091  1.00     0.0      1.00      102
*****************************************************************************
*****************************************************************************

                      INITIAL PROFILE CHEMICAL DATA

-----------------------------------------------------------------------------
  1     < Number of chemical species.  At least one must be specified
-----------------------------------------------------------------------------
 Soil layer      Chem1       Chem2       Chem3       Chem4
                 ----mg/kg dry soil----
-----------------------------------------------------------------------------
  1          0-125         0.0         0.0         000.0
  2          0-125         0.0         0.0         000.0
  3          0-125         0.0         0.0         000.0
  4          0.0251        0.0         0.0         000.0
  5          0.0251        0.0         0.0         000.0
  6          0.0251        0.0         0.0         000.0
  7          0.0120        0.0         0.0         000.0
  8          0.0129        0.0         0.0         000.0
  9          0.0129        0.0         0.0         000.0
 10          0.0080        0.0         0.0         000.0
 11          0.0080        0.0         0.0         000.0
 12          0.0086        0.0         0.0         000.0
 13          0.008         0.0         0.0         000.0
 14          0.008         0.0         0.0         000.0
 15          0.008         0.0         0.0         000.0
 16          0.008         0.0         0.0         000.0
 17          0.008         0.0         0.0         000.0
 18          0.008         0.0         0.0         000.0
-----------------------------------------------------------------------------
Concentration (mg/l) below profile, used with lower boundaries 1 or 3
                          0.0         0.0         0.0         0.0
 500      < Depth (mm) of water in mixing cell (boundaries 1 and 3 only)- Enter 0
for no mixing cell
*****************************************************************************
```

Table E.3 continued

```
*****************************************************************************
                          CHEMICAL PROPERTIES
                          -------------------
Chem                    Solubility  Vapour Density     Link        Plant
 No        Name          mg/dm3        mg/dm3                    Uptake
-------    ----          -------     ----------      --------   1(yes),0(no)
  1   '    Atrazine      .3300E+02     .2800E-06        1             1
-----------------------------------------------------------------------------
     Linear(1)                Linear Isotherm      | Freundlich Isotherm    (See
Table 3 in
Chem      or                 Kes      2-site model          Kfes  Exponent        P-
3-24 in
 No.  Freundlich(2)          1/kg     f        alpha      | (unit dependent)
manual)
----  ------                -----    ---      -------     -------   ---
  1         1                100.0    1.0      .003        100.0     1.0
-----------------------------------------------------------------------------
Diffusion coefficients: (see pages 3-5 to 3-7 in manual)
-------------------------
 120          <Molecular diffusion coefficient in water (mm2/day)
 0.001        <Adjustment in Brusker's equation (a in equation 3.10 (ver 3)
 10           <Adjustment in Brusker's equation (b in equation 3-10)
 120          <Molecular diffusion coefficient in air (mm2/day)
 14400+06 <Air diff. coeff. enhancement to account for atmospheric pressure
fluctuations
*****************************************************************************
*  The values of L1,L2--->Ln ('Link' in the Chemical Properties above)
*    determine which species form a transformation chain:
*    Setting Ln = 0 breaks the pathway, Ln = 1 restores it.
*
*                        Transformation pathways-------------------->
*          PATH 1          PATH 2          PATH 3          PATH 4
*    CH1----/L1/---->CH2-----/L2/---->CH3----/L3/---->CH4---/L4/---> .
*                                                          |
*       PATH 5          PATH 6          PATH 7          PATH 8          Degradation
*                                                                        pathways
*     v               v               v               v                    |
*  PRODUCT         PRODUCT         PRODUCT         PRODUCT                 v
*****************************************************************************
                  TRANSFORMATION AND DEGRADATION RATE CONSTANTS
-----------------------------------------------------------------------------
    1    <Rate constants apply to bulk soil (1), or solution phase only (0)
Temperature and water content effects (transformation rate constants only):
    1    <Include temperature subroutines and adjustments? yes(1), no(0)
    2    <Q10: factor by which rate constant changes per 10 C increase
   20    <Base temperature: at which rate constants below apply
   35    <Optimum temperature: Q10 relationship applies from 0 C to here
   50    <Maximum temperature: Rate constants decrease from optimum to here
 .05     <High end of optimum water content range: air-filled porosity
 -300    <Lower end of optimum water content: matric potential kPa
-1500    <Minimum matric potential for transformations kPa
  0.6    <Relative transformation rate at saturation
*****************************************************************************
          TRANSFORMATION RATE CONSTANTS (may be adjusted as specified above)
-----------------------------------------------------------------------------
Layer      Chemical 1          Chemical 2          Chemical 3          Chemical 4
 no.       ----------          ----------          ----------          ----------
          <---------------------- day ^ -1 ----------------------->
    1      0.0165E-00          0.0000E-00          0.0000E-00          0.0000E-00
    2      0.0165E-00          0.0000E-00          0.0000E-00          0.0000E-00
    3      0.0165E-00          0.0000E-00          0.0000E-00          0.0000E-00
    4      0.0165E-00          0.0000E-00          0.0000E-00          0.0000E-00
    5      0.0165E-00          0.0000E-00          0.0000E-00          0.0000E-00
    6      0.0165E-00          0.0000E-00          0.0000E-00          0.0000E-00
    7      0.0060E-00          0.0000E-00          0.0000E-00          0.0000E-00
```

Table M-3 continued

9	0.0060E-00	0.0060E-00	0.0060E-00	0.0060E-00
8	0.0060E-00	0.0060E-00	0.0060E-00	0.0060E-00
10	0.0060E-00	0.0060E-00	0.0060E-00	0.0060E-00
11	0.0060E-00	0.0060E-00	0.0060E-00	0.0060E-00
12	0.0060E-00	0.0060E-00	0.0060E-00	0.0060E-00
13	0.0060E-00	0.0060E-00	0.0060E-00	0.0060E-00
14	0.0060E-00	0.0060E-00	0.0060E-00	0.0060E-00
15	0.0060E-00	0.0060E-00	0.0060E-00	0.0060E-00
16	0.0060E-00	0.0060E-00	0.0060E-00	0.0060E-00
17	0.0060E-00	0.0060E-00	0.0060E-00	0.0060E-00
18	0.0060E-00	0.0060E-00	0.0060E-00	0.0060E-00

DEGRADATION RATE CONSTANTS (not influenced by water or temperature)

Layer no	Chemical 1	Chemical 2	Chemical 3	Chemical 4
	<-------- day ^-1 -------->			
1	0.0165E-00	0.0000E-01	0.0000E-01	0.0000E-01 0
2	0.0165E-00	0.0000E-01	0.0000E-01	0.0000E-01 0
3	0.0165E-00	0.0000E-01	0.0000E-01	0.0000E-01 0
4	0.0165E-00	0.0000E-01	0.0000E-01	0.0000E-01 0
5	0.0165E-00	0.0000E-01	0.0000E-01	0.0000E-01 0
6	0.0165E-00	0.0000E-01	0.0000E-01	0.0000E-01 0
7	0.0165E-00	0.0000E-01	0.0000E-01	0.0000E-01 0
8	0.0165E-00	0.0000E-01	0.0000E-01	0.0000E-01 0
9	0.0165E-00	0.0000E-01	0.0000E-01	0.0000E-01 0
10	0.0165E-00	0.0000E-01	0.0000E-01	0.0000E-01 0
11	0.0060E-00	0.0000E-01	0.0000E-01	0.0000E-01 0
12	0.0060E-00	0.0000E-01	0.0000E-01	0.0000E-01 0
13	0.0060E-00	0.0000E-01	0.0000E-01	0.0000E-01 0
14	0.0060E-00	0.0000E-01	0.0000E-01	0.0000E-01 0
15	0.0060E-00	0.0000E-01	0.0000E-01	0.0000E-01 0
16	0.0060E-00	0.0000E-01	0.0000E-01	0.0000E-01 0
17	0.0060E-00	0.0000E-01	0.0000E-01	0.0000E-01 0
18	0.0060E-00	0.0000E-01	0.0000E-01	0.0000E-01 0

CHEMICAL APPLICATIONS

1 < Number of broadcast applications (At least 1. Can be past last date)

Start of date (or day no.)	Incorporation (as mulch, 0 in surface)	Chem1	Chem2	Chem3	Chem4
		mg/sq m (1mg/sq m = 10kg/ha)			
63081	0	112.00	.00	.00	.00

RAIN/IRRIGATION AND WATER COMPOSITION

Choosing the steady-state flow option will prevent calls to the water flow subroutine. fix fluxes and concentrations at those specified below and maintain these constant with time. Interrupted steady-state can be specified by appropriate times and amounts. For the steady-state flow option, use a uniform soil column.

1	< Water flow: Richards (1), modified Addiscott (2), steady-state (3)
-5	< For Addiscott : matric potential at field capacity (kPa)
-300	< : division between mobile and immobile water (kPa)
0-4	< For steady-state: Water content in uniform column (theta)
40	< Number of water applications. Some or all can be past last day.

Table E 3 continued:

Start time Date or Day so	Time of day	Amount se	Surface flux density mm/d	Dissolved in water (can be 0) mg/l Chse1	Chem2	Chem3	Chse4
050691	50	07 0	200 0	0.000E+00	000E+00	.000E+00	.000E+00
050751	.07	02.0	200.0	0.000E+00	.000E+00	.000E+00	000E+00
051151	.54	13.0	200.0	0.000E+00	.000E+00	000E+00	000E+00
051551	.21	16 0	200 0	0.000E+00	.000E+00	000E+00	.000E+00
051951	.5	21 0	200 0	0.000E+00	.000E+00	.000E+00	.000E+00
052051	.5	1.0	200 0	0.000E+00	.000E+00	000E+00	.000E+00
052351	.66	0 0	200 0	0.000E+00	.000E+00	.000E+00	.000E+00
052491	.17	20-0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
052691	.542	11.0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
052751	.75	5 0	200 0	0.000E+00	.000E+00	.000E+00	.000E+00
052551	.75	14.0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
053191	.2	19.0	200 0	0.000E+00	.000E+00	.000E+00	.000E+00
060491	.542	9-0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
050551	.02	58.0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
060891	.083	15.0	200 0	0.000E+00	.000E+00	.000E+00	.000E+00
050751	.375	5.0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
051251	.213	17.0	200 0	0.000E+00	.000E+00	.000E+00	.000E+00
061551	.333	9.0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
061751	.667	3-0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
061951	62	9 0	200 0	0.000E+00	.000E+00	.000E+00	.000E+00
062191	333	19.0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
062291	.625	2.0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
052351	.525	1.0	200 0	0.000E+00	.000E+00	.000E+00	.000E+00
053451	.525	7-0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
052551	.01	1.0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
063691	.625	21-0	200 0	0.000E+00	.000E+00	.000E+00	.000E+00
062791	.65	1.0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
053551	.75	6.0	200 0	0.000E+00	.000E+00	.000E+00	.000E+00
053051	.525	2-0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
070151	.57	3.0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
070591	.70	7 0	200 0	0.000E+00	.000E+00	.000E+00	.000E+00
070891	.652	2.0	300 0	0.000E+00	.000E+00	.000E+00	.000E+00
070991	.30	26.0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
071051	.37	20-0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
071251	.75	2.0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
071451	65	1.0	200 0	0.000E+00	.000E+00	.000E+00	.000E+00
071651	.52	2-0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
071791	.65	30.0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
071991	.48	35-0	200 0	0.000E+00	.000E+00	.000E+00	.000E+00
072091	.35	1-0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
072291	.645	2.0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
072451	.30	1-0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
072591	.55	1.0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
072791	.35	10-0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
072891	.48	15-0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
072591	.55	12.0	200.0	0.000E+00	.000E+00	.000E+00	.000E+00
073091	.25	3-0	200 0	0.000E+00	.000E+00	.000E+00	.000E+00
073151	.30	29-0	200 0	0.000E+00	.000E+00	.000E+00	.000E+00

POTENTIAL ET (WEEKLY TOTALS, mm), DEPTH TO WATER TABLE (mm)
MEAN WEEKLY TEMPERATURES AND MEAN WEEKLY AMPLITUDE (degrees C)

Week no	ET	Water table	Mean temp	Amplitude
1	40 6	0	25 2	7 1
2	36 6	0.	25 7	6.0
3	41 4	0.	28 3	5.5
6	28 2	0.	26 5	4 5

Table B.3 continued

5	40.1	6	26.6	6.3
6	37.3	6.	23.5	5.6
7	46.5	6.	28.9	7.1
8	44.9	6	26.1	6.3
6	43.4	6	27.7	5.6
10	44.5	6	27.8	5.7
11	28.2	6	27.2	5.3
12	40.6	6.	26.0	6.6
13	35.5	6.	27.4	5.3

Table B 4 Weather input data file (FILEW=UFGA9101.WTH) for CERES-Sorghum (April 1 to August 31, 1991)

```
*WEATHER DATA : Gainesville,Florida,USA

@ INSI      LAT     LONG  ELEV   TAV   AMP REFHT WNDHT
  UFGA   29.630  -82.370    10  20.9   7.5  2.00  3.00
@DATE  SRAD  TMAX  TMIN  RAIN                   PAR
91091  26.4  21.7   5.0   0.0                  58.0
91092  26.1  23.9   4.4   0.0                  57.3
91093  19.6  25.6   8.9   0.0                  43.1
91094  18.9  25.6  13.3   0.3                  41.6
91095  17.2  27.2  17.2   0.0                  37.7
91096  20.3  28.9  15.0   0.0                  44.6
91097  21.2  28.9  17.8   0.3                  46.5
91098  17.9  30.0  19.4  11.9                  39.3
91099  22.9  30.0  20.0  13.5                  50.3
91100  19.0  29.4  18.3   2.5                  39.5
91101  23.2  29.4  16.1   0.0                  50.9
91102  21.7  30.6  17.2   0.0                  47.8
91103  21.4  29.4  17.8   0.0                  47.1
91104  25.8  29.6  16.1   0.3                  56.6
91105  19.4  30.6  18.3   0.0                  42.6
91106  24.8  30.0  15.6   0.0                  54.5
91107  11.3  31.7  16.7  16.3                  24.7
91108  20.4  25.6  17.8   0.0                  44.9
91109  13.8  27.8  17.2  33.0                  30.3
91110  17.5  28.9  16.7  37.6                  38.5
91111  27.7  27.8  12.2   0.0                  60.9
91112  25.2  23.3   8.3   0.0                  55.3
91113   6.1  26.7  11.7   6.6                  13.4
91114  24.5  23.9  19.4   0.0                  53.9
91115   2.4  30.6  20.0  28.2                   5.2
91116  13.3  22.8  16.7   0.0                  29.2
91117  23.5  27.8  17.2   0.0                  51.6
91118  22.3  32.2  18.3   0.0                  49.9
91119  26.3  32.8  19.4   0.0                  57.7
91120  24.2  33.3  21.1   0.0                  53.1
91121  22.2  32.8  18.9   0.0                  48.3
91122  27.5  32.2  17.2   9.1                  60.5
91123  25.6  31.7  16.1   0.0                  56.1
91124  26.2  31.7  18.3   0.0                  57.6
91125  25.5  32.2  17.2   0.0                  56.1
91126  14.9  31.7  20.0   7.0                  32.7
91127  20.3  30.6  17.2   2.0                  44.7
91128  21.8  31.1  19.4   0.0                  47.9
91129  24.8  31.1  21.1   0.0                  54.4
91130  25.0  31.1  20.6   0.0                  54.9
91131  13.5  32.2  19.4  13.0                  29.7
91132  26.4  30.0  16.1   0.0                  58.1
91133  23.9  30.6  18.9   0.0                  52.4
91134  26.0  30.0  20.6   0.0                  57.1
91135  26.3  32.2  20.0   0.0                  57.9
91136  25.6  32.8  17.8  14.0                  56.3
91137  26.4  33.3  19.4   0.0                  57.9
91138  27.5  32.8  19.4   0.0                  60.4
91139  18.3  33.3  19.4  21.8                  40.1
91140  18.2  30.6  22.2   1.0                  40.0
```

Table B.4 continued.

&DATE	SRAD	TMAX	TMIN	RAIN	PAR
91141	17.2	30.0	21.7	0.0	37.8
91142	15.0	30.0	23.3	0.0	33.0
91143	8.7	29.4	23.3	0.0	19.0
91145	11.4	27.8	20.6	22.0	25.1
91155	24.4	28.9	21.1	0.0	53.5
91146	10.0	32.8	20.6	11.0	22.0
91147	22.9	32.2	21.7	0.0	50.3
91148	25.6	32.8	21.7	0.0	55.1
91149	25.2	32.8	21.1	14.0	57.6
91150	17.6	34.4	21.7	0.0	38.7
91151	11.7	31.1	21.7	19.0	25.7
91152	22.4	32.2	17.8	0.0	49.4
91153	25.7	31.7	18.3	0.0	56.8
91154	24.8	31.1	20.5	0.0	54.8
91155	14.0	32.8	21.7	50.0	31.0
91155	10.5	32.2	20.6	15.0	50.9
91157	0.5	31.1	21.1	9.0	10.0
91158	11.1	25.0	16.1	0.0	25.5
91159	28.3	23.3	15.6	0.0	52.5
91150	25.0	29.4	17.2	0.0	55.3
91151	25.3	30.6	17.2	0.0	55.9
91162	26.7	30.0	16.7	0.0	63.4
91153	23.1	31.1	16.7	0.0	51.1
91155	22.9	31.1	17.2	0.0	50.5
91165	26.4	32.8	20.0	0.0	58.2
91155	23.9	33.9	18.5	0.0	52.9
91157	25.8	34.5	19.5	0.0	57.5
91168	23.2	34.4	19.4	3.0	51.2
91169	20.4	34.4	22.2	0.0	45.1
91170	14.6	30.0	22.2	9.0	32.3
91171	27.0	31.1	22.2	0.0	59.6
91172	25.9	33.9	21.7	0.0	57.3
91173	25.1	34.4	20.6	3.0	55.4
91174	23.9	34.4	20.6	1.0	52.8
91175	21.7	34.4	21.1	7.0	47.6
91176	25.3	34.4	20.6	1.0	55.8
91177	21.1	31.7	21.7	21.0	46.5
91178	23.7	32.2	21.1	1.0	52.4
91179	28.3	32.8	21.1	0.0	52.5
91180	13.9	33.9	21.7	5.0	30.5
91181	23.2	32.2	21.7	2.0	51.3
91182	16.8	31.7	22.8	3.0	37.2
91183	21.4	32.8	22.8	0.0	47.2
91184	25.6	32.2	22.8	0.0	56.5
91185	25.2	33.3	22.8	0.0	55.5
91186	19.1	34.4	22.2	0.0	42.1
91187	15.3	31.7	22.8	7.0	33.8
91188	26.7	32.2	19.5	0.0	58.9
91189	23.4	33.9	21.1	2.0	51.6
91190	12.1	34.4	22.2	25.0	26.7
91191	21.8	31.1	21.1	20.0	48.1
91192	11.8	32.8	21.7	0.0	26.1
91193	8.6	31.7	21.1	2.0	18.9
91195	12.8	30.0	22.8	0.0	28.3
91195	16.4	32.8	22.2	1.0	36.3
91195	20.9	33.9	22.2	0.0	46.1
91197	21.0	32.2	22.2	2.0	46.4
91198	18.6	33.3	21.7	38.0	41.6
91199	18.9	33.3	21.1	0.0	41.6

Table 8.4 continued.

@DATE	SRAD	TMAX	TMIN	RAIN	PAR
91200	20.8	31.1	21.7	39.0	44.2
91201	19.4	35.0	21.1	1.0	42.7
91202	23.7	33.3	20.8	0.0	52.3
91203	23.1	33.9	22.2	1.0	51.1
91204	18.0	35.0	22.2	0.0	35.8
91205	22.4	33.9	22.8	1.0	49.5
91206	18.5	31.7	21.1	1.0	40.8
91207	14.2	32.2	21.1	10.0	31.4
91208	17.0	31.7	20.0	0.0	37.5
91209	20.2	32.2	21.1	14.0	44.5
91210	14.0	30.8	21.7	12.0	31.0
91211	12.6	31.1	21.7	3.0	27.7
91212	11.9	30.8	20.8	29.8	26.3
91213	12.3	30.6	20.8	37.8	28.5
91214	21.1	28.5	21.1	3.3	45.4
91215	20.5	31.1	20.8	2.0	44.3
91216	23.9	32.2	21.1	0.5	51.5
91217	16.9	32.8	22.2	2.0	38.5
91218	24.4	33.3	21.1	1.8	52.8
91219	27.4	34.4	20.6	0.0	57.3
91220	17.3	35.0	23.3	0.0	37.3
91221	15.4	35.0	22.2	1.8	33.6
91222	20.9	33.3	21.7	0.0	45.1
91223	22.2	33.3	21.1	4.1	47.9
91224	21.9	34.4	22.0	0.0	47.1
91225	24.9	32.2	21.1	1.3	53.7
91226	22.7	34.4	21.1	0.0	49.0
91227	15.9	33.3	20.0	0.0	34.2
91228	22.2	32.2	19.4	15.5	47.9
91229	25.3	34.4	20.4	0.0	54.9
91230	15.8	33.9	19.4	0.0	42.7
91231	14.1	32.2	21.1	0.0	30.5
91232	11.4	30.8	22.2	3.8	24.8
91233	24.7	28.9	21.7	0.3	53.1
91234	17.2	33.3	15.4	0.0	37.0
91235	16.2	32.8	21.7	0.0	35.0
91236	10.9	32.8	21.1	13.7	23.5
91237	17.2	30.8	21.1	3.3	37.0
91238	20.2	32.2	21.1	0.0	43.5
91239	16.4	33.3	21.1	89.8	35.2
91240	16.4	32.2	21.7	17.0	35.3
91241	15.8	32.8	21.7	16.3	34.0
91242	12.0	30.8	21.7	0.0	25.9
91243	25.1	32.2	20.8	0.5	54.0

Table A-5 CERES-Sorghum input data file (File-X) for minimum data set

```
*EXP.DETAILS: UFGA9101SG NITROGEN/IRRIGATION RATE ON SORGHUM

*GENERAL
@PEOPLE
 O.S. MBUYA, K.J. BOOTE AND P. NKEDI-KIZZA
@ADDRESS
 404 NEWELL HALL, UNIVERSITY OF FLORIDA, GAINESVILLE, FLORIDA 32611, USA
@SITE
 UF GA
@ PAREA  PRNO  PLEN  PLDR  PLSP  PLAY HAREA  HRNO  HLEN HARM.........
  196.0    15  14.0   -99   -99       10.0   -99 -99.0 Hand harvest

*TREATMENTS                        -------------FACTOR LEVELS-------------
@N R O C TNAME.................. CU FL SA IC MF MI MF MR MC MT ME MH SM
 1 0 0 0 LOW N X DPT. IRRIG.     1  1  0  1  1  1  1  0  0  0  0  0  1
 2 0 0 0 LOW N X NDO. IRRIG.     1  1  0  1  1  2  1  0  0  0  0  0  1
 3 0 0 0 LOW N X RAINFED         1  1  0  1  1  0  1  0  0  0  0  0  1
 4 0 0 0 HIGH N X DPT. IRRIG     1  1  0  1  1  1  2  0  0  0  0  0  1
 5 0 0 0 HIGH N X NDO. IRRIG     1  1  0  1  1  2  2  0  0  0  0  0  1
 6 0 0 0 HIGH N X RAINFED        1  1  0  1  1  0  2  0  0  0  0  0  1

*CULTIVARS
@C CR INGENO CNAME
 1 SG IS0051 SAVANNA 5

*FIELDS
@L ID_FIELD WSTA....  FLSA  FLOB  FLDT  FLDD  FLDS  FLST SLTX  SLDP
 1D SOIL
 1 UFGA9101 UFGA      -99     0 DR000     0     0 00000   FSA    90
1SSG910015

*SOIL ANALYSIS
@A SADAT  SMHB  SMPX  SMKE
 1   -99   -99   -99   -99
@A SADAT  SMHB  SMPX  SMKE
 2       SA001 SA001 SA001

*INITIAL CONDITIONS
@C   PCR ICDAT  ICRT  ICND  ICRN  ICRM
 1    SG 91106   500   -99  1.00  1.00
@C  ICBL  SH2O  SNH4  SNO3
 1     5 0.086  0.08  0.08
 1    15 0.086  0.08  0.08
 1    30 0.086  0.08  0.08
 1    45 0.086  0.08  0.08
 1    60 0.086  0.08  0.08
 1    90 0.076  0.08  0.08

*PLANTING DETAILS
@P PDATE EDATE  PPOP  PPOE  PLME  PLDS  PLRS  PLRD  PLDP  PLWT  PAGE
PENV  PLPH
 1 91112 91116  20.0  20.0     S     R    90     0   5.0   -99   -99
-99.0   1.0
```

Table B.5 continued

```
*IRRIGATION AND WATER MANAGEMENT
@I  EFIR  IDEP  ITHR  IEPT  IOFF  IAME  IAMT
 1   1.00   -99   -99   -99   -99   -99   -99
@I IDATE  IROP  IRVAL
 1 91123 IR004  12.7
 1 91163 IR004  16.9
 1 91166 IR004  16.9
 1 91172 IR004  19.9
 2 91123 IR004  12.7
 2 91172 IR004  19.0

*FERTILIZERS (INORGANIC)
@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD
 1 91107 FE017   -99     5    50   -99   -99   -99   -99   -99
 1 91114 FE017   -99     5    25   -99   -99   -99   -99   -99
 1 91155 FE017   -99     5    25   -99   -99   -99   -99   -99
 2 91107 FE017   -99     5   150   -99   -99   -99   -99   -99
 2 91114 FE017   -99     5    75   -99   -99   -99   -99   -99
 2 91155 FE017   -99     5    75   -99   -99   -99   -99   -99

*HARVEST DETAILS (J = 1)
@H HDATE
 1 91212

*SIMULATION CONTROLS
@N GENERAL     NYERS NREPS START SDATE RSEED SNAME
 1 GE              1     1     S 91106  2150 MAUYA
@N OPTIONS     WATER NITRO SYMBI PHOSF POTAS DISES
 1 OP              Y     Y     N     N     N     N
@N METHODS     WTHER INCON LIGHT EVAPO INFIL PHOTO
 1 ME              M     M     E     R     S     C
@N MANAGEMENT  PLANT IRRIG FERTI REBID HARVE
 1 MA              R     R     R     N     R
@N OUTPUTS     FNAME OVVEW SUMRY FROPT GROUT CAOUT WAOUT WIOUT MIOUT
DIOUT  LONG
 1 OU              N     Y     Y     3     Y     N     Y     Y     N
Y     M

@  AUTOMATIC MANAGEMENT
@N PLANTING    PFRST PLAST PFAGE PFAGL PFAGD PSTMX PSTMN
 1 PL            155   200    40   100    30    40    10
@N IRRIGATION  IMDEP ITHRL ITHRU IROFF IMETH IRAMT IREFF
 1 IR             30    50   100 GS000 IR001   10  1.00
@N NITROGEN    NMDEP NMTHR NAMNT NCODE NAOFF
 1 NI             30    50    25 FE001 GS000
@N RESIDUES    RIPCN RTIME RIDEP
 1 RE            100     1    20
@N HARVEST     HFRST HLAST HPCNP HPCNR
 1 HA              0   365   100     0
```

Table B-8 Soil data parameters used to calculate water characteristics in diffrent soils

*SOILS

1 Calculations from the limits algorithms lead to the following:

	SLTX	SLLL	SRGF	SSAT	SRGF	SSKS	SBDM	SLOC	SLCL	SLSI	SLCF	SLNI
	CL	.32	.36	.29	1	1.0	1.3	1.5	60	20	0	.12
	SICL	.20	.28	.39	1	1.0	1.1	1.5	20	45	0	.12
	CLLO	.21	.23	.28	1	1.0	1.1	1.3	22	30	0	.12
	SCLLO	.19	.32	.36	1	1.0	1.3	1.2	30	60	0	.11
	SACLL	.19	.29	.36	1	1.0	1.3	1.2	20	10	0	.12
	SI	.17	.31	.26	1	1.0	1.2	1.2	5	82	0	.12
	LO	.15	.27	.39	1	1.0	1.2	1.2	20	40	0	.12
	SILO	.18	.22	.33	1	1.0	1.4	1 2	10	80	0	.12
	SALO	.18	.21	.28	1	1.0	1.5	0 7	10	30	0	.07
	LOSA	.08	.17	.29	1	1.0	1.5	0.2	5	15	0	.02
	SA	.04	.10	.12	1	1.0	1.7	0.2	5	5	0	.03

CRITICAL LIMITS OF SOIL WATER AVAILABILITY FOR VARIOUS BULK DENSITIES (Ritchie)

SAND	CLAY CONTENT -- PERCENT											
	0		10		20		40		60		70	
PCT	LL	DUL	LL	DUL	LL	DUL	LL	DUL	LL	DUL	LL	DUL
V												
						BULK DENSITY = 1.1						
0	.07	.20	.09	.22	.11	.24	.12	.27	.12	.29	.17	.31	.19	.33	.22	.22
10	.05	.10	.07	.21	.00	.23	.11	.25	.14	.27	10	30	10	22	.20	34
20	.04	17	06	.20	.08	.22	.10	.24	.12	.26	15	28	17	28	.18	32
30	.02	.10	05	.10	.07	.20	.00	22	.11	.22	.13	27	15	20	.17	.31
40	.02	12	02	.17	.05	10	07	21	10	22	.12	22	16	.28		
50	.02	.13	02	.15	.04	.18	.00	.20	.08	.22	.10	.24				
60	.02	.12	02	.14	.03	.14	02	.18	.07	.20						
70	02	10	02	12	02	12	03	17								
80	02	00	02	11	02	12										
90	02	00	02	.10												
100	.02	.00														
						BULK DENSITY = 1.2						
0	.00	.22	.11	.24	.12	.27	.12	.29	.18	.21	.20	34	22	36	.25	.38
10	.07	.20	09	.23	12	.25	14	26	16	.30	10	32	21	.35	.23	37
20	.05	10	06	21	10	.24	12	26	15	.26	.17	31	10	33	22	35
30	.04	.17	.04	.20	.04	.22	11	.24	.13	.27	.16	.26	16	32	.20	.24
40	.02	.10	.05	.16	.07	.21	.00	.23	.12	.25	.14	.20	10	.30		
50	.02	.14	02	.17	00	10	00	21	10	.24	12	20				
60	.01	12	02	12	.04	.10	.00	.20	.00	.22						
70	.02	.11	02	.14	02	.10	.05	16								
80	.02	.10	.02	12	02	.15										
90	.02	.00	02	.11												
100	02	07														
						BULK DENSITY = 1.2						
0	.10	.24	.12	26	12	.28	10	21	.20	.24	.23	37	25	.26	26	.42
10	.00	22	12	.25	14	.27	16	26	.18	.32	21	22	24	.27	20	40
20	.07	21	00	.23	12	26	15	26	.17	.21	.20	22	22	26	.22	28
30	02	18	08	21	10	24	13	27	.15	20	10	32	21	34	.23	37
40	.04	.17	.00	20	09	22	11	22	14	27	10	20	10	33		
50	01	10	.02	16	07	21	10	23	12	20	.15	.20				
60	.02	14	02	.17	.05	10	00	22	11	24						
70	02	12	.02	12	.04	.17	00	20								
80	02	11	02	12	02	10										
90	02	00	02	12												
100	02	07														

Table B.6 continued

	BULK DENSITY = 1.4															
1 0	.12	.26	.15	.28	.10	.31	.20	.34	.23	.37	.24	.35	.28	.42	.29	.42
1 10	.14	.24	.13	.27	.16	.29	.18	.32	.21	.35	.24	.38	.27	.40	.28	.42
1 20	.08	.22	.11	.25	.14	.28	.17	.30	.19	.33	.22	.36	.25	.39	.28	.41
1 30	.07	.20	.05	.23	.12	.26	.15	.25	.18	.31	.20	.34	.23	.37	.26	.40
1 40	.05	.15	.06	.21	.10	.24	.13	.27	.16	.30	.15	.32	.21	.35		
1 50	.03	.17	.06	.20	.09	.22	.11	.25	.14	.28	.17	.31				
1 60	.02	.15	.04	.18	.07	.21	.10	.23	.12	.26						
1 70	.02	.13	.02	.16	.05	.15	.08	.22								
1 80	.02	.12	.02	.14	.03	.17										
1 90	.02	.10	.02	.12												
1100	.02	.08														

	BULK DENSITY = 1.5															
1 0	.14	.27	.17	.30	.20	.33	.23	.36	.26	.38	.26	.36	.26	.38	.27	.38
1 10	.12	.26	.15	.28	.18	.31	.21	.34	.24	.37	.25	.38	.28	.38	.27	.38
1 20	.10	.24	.13	.27	.16	.30	.19	.32	.22	.35	.25	.38	.25	.38	.26	.38
1 30	.08	.22	.11	.25	.14	.28	.17	.31	.20	.34	.23	.36	.25	.38	.26	.38
1 40	.05	.20	.05	.23	.12	.26	.15	.29	.18	.32	.21	.35	.24	.20		
1 55	.04	.18	.07	.21	.10	.24	.13	.27	.16	.30	.19	.33				
1 60	.03	.16	.05	.19	.08	.22	.11	.25	.14	.28						
1 70	.02	.14	.04	.17	.06	.20	.05	.23								
1 80	.02	.12	.02	.15	.05	.18										
1 90	.02	.10	.02	.13												
1100	.02	.05														

	BULK DENSITY = 1.6															
1 0	.16	.29	.19	.32	.21	.35	.22	.35	.23	.35	.24	.35	.25	.35	.26	.35
1 10	.14	.27	.17	.30	.20	.34	.22	.35	.22	.35	.22	.35	.24	.35	.25	.35
1 20	.12	.25	.15	.28	.18	.32	.21	.35	.22	.35	.23	.35	.24	.35	.25	.32
1 30	.10	.23	.13	.26	.18	.30	.19	.33	.21	.35	.22	.35	.23	.35	.24	.35
1 40	.08	.21	.11	.24	.16	.27	.17	.31	.20	.34	.22	.35	.23	.35		
1 50	.06	.19	.09	.22	.12	.25	.15	.25	.16	.32	.21	.35				
1 60	.04	.17	.07	.20	.10	.23	.13	.27	.16	.30						
1 70	.02	.15	.05	.18	.08	.21	.11	.25								
1 80	.02	.13	.03	.16	.06	.19										
1 90	.02	.11	.02	.14												
1100	.02	.09														

	BULK DENSITY = 1.7															
1 0	.10	.31	.10	.31	.15	.31	.20	.31	.21	.31	.22	.31	.23	.31	.24	.31
1 10	.15	.29	.10	.31	.19	.31	.20	.31	.21	.31	.22	.31	.23	.31	.24	.31
1 20	.13	.27	.12	.30	.19	.31	.19	.31	.20	.31	.21	.31	.22	.31	.23	.31
1 30	.11	.25	.14	.28	.10	.31	.10	.31	.15	.31	.20	.31	.21	.31	.22	.31
1 40	.09	.23	.12	.26	.16	.29	.10	.31	.15	.31	.20	.31	.21	.31		
1 50	.07	.20	.10	.24	.13	.27	.17	.30	.10	.31	.15	.31				
1 60	.05	.18	.08	.22	.11	.25	.15	.28	.18	.31						
1 70	.03	.16	.06	.15	.05	.23	.13	.26								
1 80	.02	.14	.04	.17	.07	.21										
1 90	.02	.12	.02	.15												
1100	.02	.10														

	BULK DENSITY = 1.8															
1 0	.16	.28	.17	.28	.10	.28	.15	.28	.20	.28	.21	.28	.22	.28	.23	.28
1 10	.15	.28	.16	.28	.17	.28	.18	.28	.19	.28	.20	.28	.21	.28	.22	.28
1 20	.14	.28	.15	.28	.10	.28	.17	.28	.18	.28	.19	.28	.21	.28	.22	.28
1 30	.13	.26	.15	.28	.16	.28	.17	.28	.18	.28	.19	.28	.20	.28	.21	.28
1 40	.10	.24	.14	.27	.13	.28	.16	.28	.17	.28	.18	.28	.19	.28		
1 50	.08	.22	.12	.25	.14	.28	.15	.28	.16	.28	.17	.28				
1 60	.06	.19	.09	.23	.13	.26	.15	.28	.16	.28						
1 70	.03	.17	.07	.21	.11	.24	.14	.28								
1 80	.02	.15	.05	.10	.06	.22										
1 90	.02	.13	.02	.16												
1100	.02	.10														

Table B 6 continued.

```
| - - - - - - - - - - - - - - - - BULK DENSITY g 1-0 - - - - - - - - - - - - - - - -
|  0   | .14  .25  .15  .25  .16  .29  .17  .25  .18  .25  .19  .25  .20  .25  .21  .29
| 10   | .13  .25  .14  .25  .15  .25  .16  .29  .17  .25  .19  .29  .20  .25  .21  .29
| 20   | .12  .29  .13  .25  .14  .29  .16  .25  .17  .29  .18  .25  .19  .29  .20  .29
| 30   | .12  .25  .13  .25  .14  .29  .15  .25  .16  .29  .17  .25  .18  .29  .19  .25
| 40   | .11  .25  .12  .29  .13  .25  .14  .29  .15  .25  .16  .29  .17  .25
| 50   | .09  .23  .11  .25  .12  .25  .13  .29  .15  .25  .16  .29
| 60   | .07  .20  .11  .24  .12  .29  .12  .25  .14  .29
| 70   | .04  .10  .09  .22  .11  .25  .12  .25
| 80   | .02  .16  .06  .19  .09  .23
| 90   | .02  .12  .03  .17
|100   | .02  .11
```

```
*1BSCS10019  SCS          FSA      90 Millhopper Fine Sand
9SLT0          COUNTRY          LAT      LONG SCS FAMILY
 Gainesville 0SA              29 630  -02 370 Loamy silic,hyperth Grass. Salaquults
@ SCOM   SAL0   SLS1   SLDR   SLR0   SLWF   SLPF   0MEH   SMPX   SMKE
    -99   0.16    9.0   0.90   56.0   1.00   0.92 15001 1X001 1X001
@SLB  SLHO  SLLL  SDUL  SSAT  SRGF  SSKE  BRDM  SLBC  SLCL  SLS1  SLCF  SLH1  SLWS  SLES  SCEC
   5 -99 0.022  0.086  0.230  1.000   7.4  1.26  0.90   -99   -99   -99   -99   -99   -99   -99
  15 -99 0.022  0.086  0.230  1.000   7.4  1.40  0.69   -99   -99   -99   -99   -99   -99   -99
  30 -99 0.023  0.086  0.226  0.590  15.0  1.45  0.29   -99   -99   -99   -99   -99   -99   -99
  45 -99 0.023  0.086  0.226  0.320  28.0  1.46  0.28   -99   -99   -99   -99   -99   -99   -99
  60 -99 0.022  0.086  0.230  0.320  28.0  1.47  0.20   -99   -99   -99   -99   -99   -99   -99
  90 -99 0.021  0.076  0.230  0.380  27.6  1.43  0.09   -99   -99   -99   -99   -99   -99   -99
```

BIOGRAPHICAL SKETCH

Odemari Stephen Mbuya was born on September 12, 1956 in Kilimanjaro, Tanzania. He received his primary education at Himo Primary School (1964-1970), after which he joined Lyamungu Secondary School (1971-1974) for his Ordinary Level secondary education. From 1975 to 1976 he attended Moshi High School for his Advanced Level secondary education with emphasis in biology, physics, chemistry and mathematics. In 1977 he served in the National Service for one year and then enrolled in a two-year diploma course in Crop Production (1978-1980) at the Ministry of Agriculture Training Institute, Ukiriguru, Mwanza. He was then employed by the Ministry of Agriculture as an agricultural extension officer in Tabora from 1980 to 1981.

Odemari joined the University of Dar-es Salaam and then Sokoine University of Agriculture in Tanzania in December, 1981 where he pursued a Bachelor of Science degree in agriculture, with a major in crop science.

He worked as a research agronomist with the Tanzania Agricultural Research Organization, heading the agronomy section of the National *Phaseolus* Bean Research Programme from 1985 to 1987. After three years of research work on bean and bean/maize intercrops, he was granted a scholarship by Centro Internacional de Agricultura Tropical (CIAT) under the SADCC/CIAT Regional Bean Programme for Southern Africa, to pursue a Master of Science degree in Agronomy.

He was admitted to Graduate School at the University of Florida in January, 1988 and graduated in May 1990 with a Master of Science degree in agronomy For a short time after graduation he worked at the University of Florida in the Departments of Agronomy, Agricultural Engineering, and Soil and Water Science as part of practical training from May to November, 1990 after which he returned briefly to Tanzania.

In February, 1991 he returned to the University of Florida to start a doctorate degree Odemari is married to Jane and they have two children Ngina and Amanda.

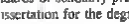
I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy

Kenneth J Boote, Chair
Professor of Agronomy

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy

Peter Nkedi Kizza, Cochair
Associate Professor of Soil and Water Science

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality as a dissertation for the degree of Doctor of Philosophy

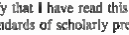


James W. Jones
Professor of Agricultural and Biological Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy

Clifton Hiebsch
Associate Professor of Agronomy

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy



Peter Hildebrand
Professor of Food and Resource Economics

This dissertation was submitted to the Graduate Faculty of the College of Agriculture and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy

August, 1996

Jack L Fry

Dean, College of Agriculture

Dean, Graduate School